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Environmental Variables of Northern California Lagoons and Estuaries and the Distribution of Tidewater Goby (*Eucyclogobius newberryi)*

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Table of Contents

List of Tables

List of Figures

List of Appendices

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Abstract. Northern California lagoon and estuary habitats were sampled in summer and early fall 1996 and 1997 to describe the relation of microhabitat variables to the distribution of tidewater goby. Twenty of the then twenty-one historically known locations for the species north of San Francisco Bay were sampled. Presence of tidewater goby was re-confirmed at 12 of the 20 sites visited. Little correlation was found between presence or absence of tidewater goby and point measurements of salinity, dissolved oxygen, temperature, pH vegetation and substrate). Relatively high catch rates of tidewater gobies occurred at some sites characterized as having environmental conditions outside the range of those reported as optimal in the literature. For example, this study found tidewater goby in water with dissolved oxygen concentrations less than 1 mg/l at Rodeo Lagoon; salinities less than 5 ppt at Lake Earl, Davis Lake, and Salmon Creek; and hyper-saline water as high as 37.9 ppt in the upper portion of Estero Americano. Infrequent but occasional connectivity to tidal fluctuation appeared to increase the likelihood of encountering tidewater goby, regardless of water quality and habitat conditions encountered in these predominantly tidally-isolated waters. This suggests that descriptive measures of physical characteristics like substrate and vegetation and point measurements of water quality provide limited insight to a water body's suitability for tidewater goby. Rather than indicate inherent habitat preferences for the species, the range of physical and water quality parameters associated with tidewater goby presence reported in much of the existing literature may simply reflect an underlying distribution of these variables in waters that have a breaching or connectivity regime that supports tidewater goby. I suggest that tidewater goby habitat needs would be more accurately described by descriptions of breaching regime, volumetric exchange, and frequency of connectivity to marine-source waters.

Introduction

The tidewater goby *Eucyclogobius newberryi* is endemic to brackish lagoons and estuaries of coastal California from the Smith River in Del Norte County to Agua Hediona Lagoon in San Diego County (Swift et al. 1989). In 1994, tidewater goby were thought to remain in only 46 of the 87 then-known historic locations along the coast of California (USFWS 1994). Because of the disappearance of the goby from many of its historic habitats and the apparent vulnerability of remaining populations, the U.S. Fish and Wildlife Service (Service) listed the tidewater goby as Endangered under the Endangered Species Act (USFWS 1994).

Since their listing as Endangered in 1994, tidewater goby have been rediscovered in some locations where the species was believed to be extirpated, and discovered in previously unknown locations, bringing to 134, the total number of locations with a known historic presence of the species of which 111 are considered still extant (USFWS 2005). In 1999, the Service proposed to identify tidewater goby in Orange and San Diego Counties as a distinct population segment (DPS; Endangered Species Act, 16 U.S.C. 1531 et seq..), and to de-list populations of the species north of Orange County citing discovery/rediscovery of several populations, the species' apparent ability to recolonize former habitats, and determination that threats to the species were less severe than perceived at the time of listing (USFWS 1999). In 2000, the Service designated critical habitat (Endangered Species Act, 16 U.S.C. 1532 (5))for the tidewater goby, but only in Orange and San Diego Counties within the DPS that was to remain listed under the Service's 1999 proposal (USFWS 2000). However, the proposal to de-list was withdrawn in 2002, stating that conclusions regarding the perceived persistence of the populations and their ability to recolonize were premature (USFWS 2002). A final recovery plan for the species was subsequently released by the Service early in 2006 (USFWS 2005).

Tidewater goby are reported to prefer a relatively narrow range for certain environmental variables, but can tolerate a broad range of habitat conditions (Table 1). Most of the habitat preference data for tidewater goby presented in the literature were derived from studies conducted south of San Francisco Bay. General habitat use characteristics reported in the literature include: salinities less than or equal to 10 parts per thousand (ppt; Swift et al. 1989) with a preference for salinities of 10 to 15 ppt (Capelli 1997); water temperatures ranging from 8.5-9° centigrade (C) in winter (Wang 1984; Swift et al.

Table 1. A sample of the range of reported preference and range of tolerance or observation exhibited by tidewater goby for various environmental attributes.

Variable	Preference	Tolerance, suitability, or range of observation
Salinity	< 5 ppt (Wang and Keegan 1988); ≤ 10 ppt (Swift et al. 1989); < 10 ppt (USFWS 1994, 2000, 2002); 10-15 ppt (Capelli 1997); 0 to 10 ppt (Swenson 1999); < 12 ppt (USFWS 2005)	Tolerant 0-41 ppt (Swift et al. 1989); Observed up to 27 ppt (Worcester 1992); Observed 2-27 ppt (Swenson 1995); Observed 1-28 ppt (Swenson and McCray 1996); Tolerant up to 54 ppt (Worcester and Lea 1996); Suitable 5-20 ppt (Capelli 1997); Tolerant freshwater to 51 ppt (USFWS 2000); Suitable up to 28 ppt (USFWS 2005)
Dissolved oxygen	Reduced oxygen levels suboptimal (Capelli 1997); Well oxygenated water required and tidewater goby disappear from lagoon areas that stagnate or stratify (Moyle 2002)	May be able to breath air and survive anoxic events (Swift et al. 1994); Tolerant of low levels (USFWS 1999)
Substrate (for breeding)	Sand (Swift et al. 1989); Sand preferred over mud in laboratory setting (Swenson 1995)	Mud may be used by wild populations if sand is less available (Swenson 1995)

1989) to 27°C in summer (Irwin and Soltz 1984); dissolved oxygen concentrations of 4-19 milligrams per liter (mg/l) (Irwin and Soltz 1984); and pH of 6.8-9.5 (Wang 1984). Tidewater gobies have been found primarily at depths of less than 1 meter (m), though deeper water has rarely been sampled (Swift et al. 1989). Irwin and Soltz (1984) reported tidewater goby in stream sections and near-shore areas of lagoons (i.e. depths of 0.25-1.0 m), and that the species does best in water that is not stagnant but rather slow moving or fairly still. Trihey and Associates (1996) found the species to be most abundant over a mucky substrate and in submerged aquatic vegetation. While tidewater goby breeding burrows have been observed in mud, they appear to prefer to construct them in sand (Swift et al. 1989, Swenson 1995). Tidewater goby are reported to require well oxygenated water (Moyle 2002) and to be impacted by reduced oxygen levels (Capelli

1997). Nutrient enrichment from agricultural or sewage effluents is suspected by some researchers to detrimentally impact tidewater goby through algal blooms and de-oxygenation of lagoons (Swift et al. 1989; Trihey and Associates 1996).

This study was initiated in 1996 to determine water quality and physical habitat parameters associated with tidewater goby distribution in northern California where little previous work had been done. In 1997, four locations were repeatedly sampled to gain insight as to consistency of tidewater goby detection and water quality point measurements between visits. Results from this study will enhance the ability of natural resource managers to correctly identify current and potential tidewater goby habitats, as needed for consultation. A better understanding of the requirements for the species will also help managers implement habitat restoration actions to aid recovery of the species.

Study Area

In 1996, there were 21 estuarine locations (including three general areas within Humboldt Bay) along the California coast with a recorded historic presence of tidewater goby north of the entrance to San Francisco Bay (Figure 1). With the exception of Virgin Creek in Mendocino County, I visited each of these locations in July through October 1996. Virgin Creek was omitted because California Department of Fish and Game (CDFG) sampled the lagoon in 1996. In 1997, I revisited eight of the sites that sampled positive for tidewater goby in 1996 to confirm that goby were still detectable, and sampled Lake Earl, Stone Lagoon, Big Lagoon, and Estero Americano repeatedly during the allowed July-October period of my Federal 10a1A collection permit.

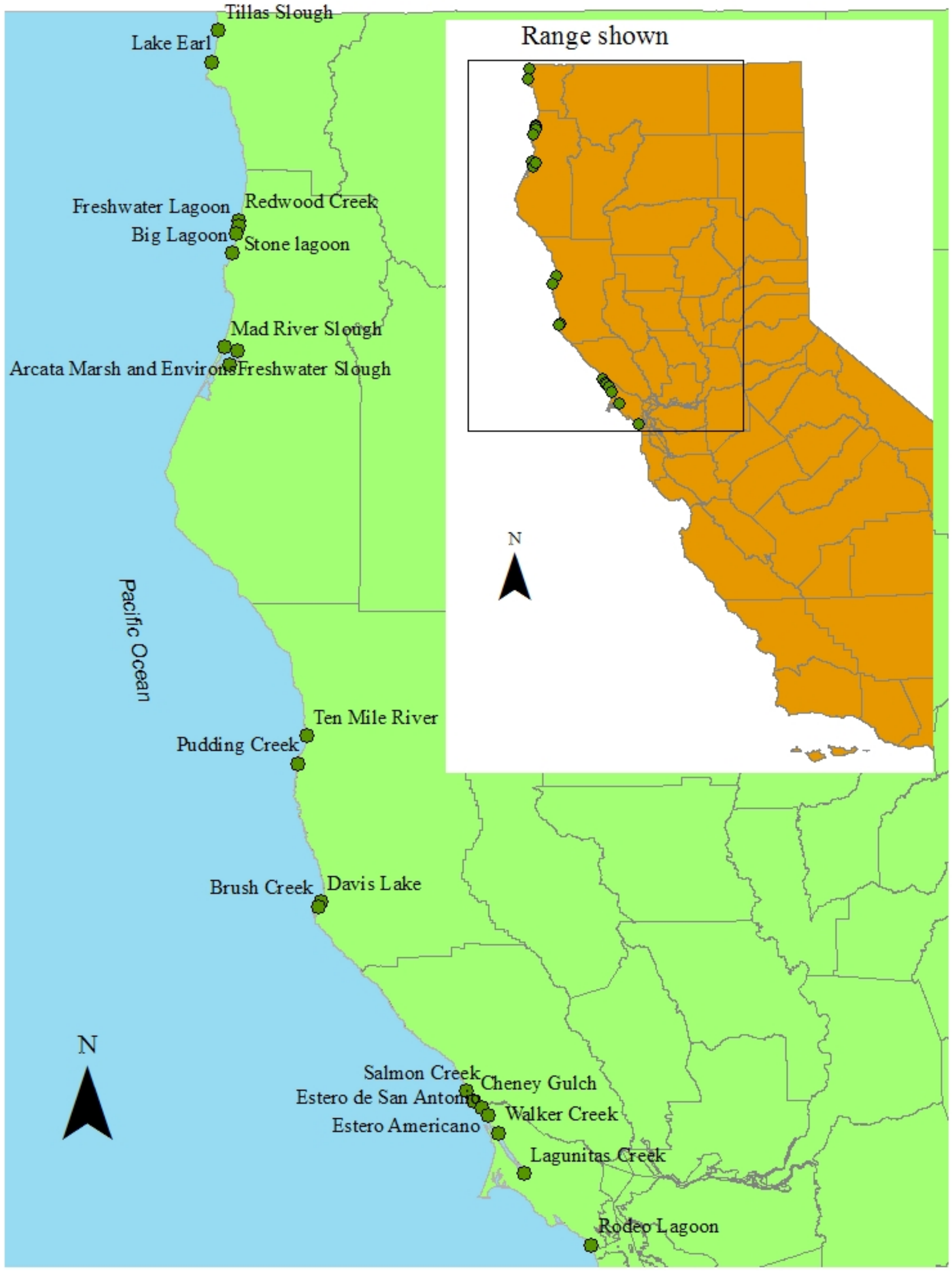

Figure 1. Range of survey conducted in 1996. All but one of the known locations within this range with a historic record of tidewater goby were visited July through October 1996. Virgin Creek in Mendocino County was sampled in 1996 by California Department of Fish and Game and was omitted from this survey.

Water body descriptions

Portions of the water body descriptions below are from the U.S. Fish and Wildlife Service Recovery Plan for Tidewater Goby (USFWS 2005):

Del Norte County:

Tillas Slough, Smith River Estuary - The available tidewater goby habitat encompasses approximately 2 to 3 hectares (5 to 7.5 acres) but there may be as much as 200 hectares (500 acres) of habitat in the Smith River estuary. All land adjacent to Tillas Slough is privately owned. The area where tidewater gobies have been detected is small and immediately down channel from a metal culvert crossing. Although connected hydrologically to the Smith River estuary, this site is the only recorded location of tidewater gobies in the Smith River watershed. At the time of sampling, the Smith River Estuary was open to the ocean and the portion of Tillas Slough sampled was within daily tidal amplitudes, with the uppermost sample site only tidally influenced during high tide. An extensive part of the slough is located on private land upstream of the sampled area that was inaccessible during this study.

Lake Earl - Lake Earl and Lake Talawa are two connected arms of the same coastal lagoon (hereafter referred to collectively as Lake Earl), ranging in size from about 1,000 to 1,950 hectares (2,500 to 4,800 acres) depending on existing water level. Much of this coastal lagoon is within the Lake Earl Wildlife Area managed by the CDFG and California State Parks and Recreation, and large portions of the shoreline are under private ownership. The sand spit was closed during all sampling.

Humboldt County:

Redwood Creek Estuary - The available tidewater goby habitat encompasses 1.0 to 4.0 hectares (2.5 to 10 acres). The site is managed by Redwood National and State Parks and private landowners. Levees were constructed around this estuary in 1968. Tidewater gobies were last detected at this location in 1980. The sand spit was only partially open during sampling which muted tidal influence, and some sample sites were located in a northern slough channel where there was further isolation from tidal influence.

Freshwater Lagoon - This coastal lagoon encompasses approximately 100 hectares (250 acres). Redwood National and State Parks controls about 10 percent of the area, California Department of Transportation controls the sand spit and highway separating Freshwater Lagoon from the ocean, and the remaining area is in private ownership. This lagoon no longer breaches as its only remaining connection to the ocean is through a box culvert under U.S. Highway 101, constructed across the sand spit in the early 1950's. Tidewater gobies were last collected at this location in 1951.

Stone Lagoon – The total size of Stone Lagoon is approximately 270 to 300 hectares (675 to 750 acres). Dry Lagoon State Park controls about 60 percent of the area, with about 40 percent in private ownership. The sand spit was closed during all sampling.

Big Lagoon – This is a large coastal lagoon measuring 700 to 800 hectares (1,750 to 2,000 acres). Big Lagoon County Park controls about 5 percent of the area, Big Lagoon Rancheria about 5 percent, Dry Lagoon State Park about 30 percent, and the remaining is under private or corporate ownership. The sand spit was closed during all sampling.

Humboldt Bay

Arcata Marsh and environs - This locality encompasses approximately 200 to 400 hectares (500 to 1,000 acres). Sample sites were selected in Klopp Lake (limited tidal connection), Butcher's Slough (fully tidal), the KATA Radio Tower vicinity (muted tidal influence), and Jacoby Creek (full to muted tidal influence); all of which drain into the northeast portion of Humboldt Bay.

Mad River Slough – Mad River Slough is located in the northwest portion of Humboldt Bay. Sample sites were dispersed within the slough only and were fully tidal; no samples were collected on the lee side of levees.

Freshwater and Faye Sloughs – Freshwater Slough enters Humboldt Bay immediately north of Eureka, California. Faye Slough enters the Freshwater Slough channel and wraps around the Murray Field Airport. Tidewater goby were detected in a mitigation marsh adjacent to Freshwater Slough in the early 1980's. Sample sites were dispersed within the slough portions only and were fully tidal; no samples were collected on the lee side of levees.

Mendocino County:

Ten Mile River - Available tidewater goby habitat at the Ten Mile River location encompasses approximately 30 to 50 hectares (75 to 100 acres). This locality is privately owned except for highway right-of-way and a small portion of State parks. The sandbar at this location was not completely closed and the estuary was partially tidal when samples were collected in both 1996 and 1997.

Pudding Creek - The available tidewater goby habitat encompasses approximately 5 to 6 hectares (12.5 to 15 acres). About 45 percent of this locality occurs in McKerricher State Beach, 45 percent is managed by the City of Fort Bragg, and the remaining 10 percent is privately owned. The sand spit was closed during all sampling.

Davis Lake - The available tidewater goby habitat encompasses approximately 1.0 to 3.1 hectares (2.6 to 7.7 acres) about 1.0 miles north of Brush Creek on the border of Manchester State Beach. The sand spit was closed during all sampling. Water levels were relatively low compared to the high water mark visible at time of sampling, and the waters sampled were not all contiguous, though they are contiguous at higher water levels.

Brush Creek - The available tidewater goby habitat encompasses approximately 0.2 to 0.5 hectare (0.5 to 1.2 acres). About 75 percent of this locality occurs in Manchester State Beach and the rest is privately owned. Tidewater gobies were last collected at this location in 1990. The sand spit was closed and this site did not form a classic estuary or lagoon when sampling occurred. All habitat was creek-like and water at the terminal end flowed onto the beach where it went subterranean.

Sonoma County:
Salmon Creek - The available tidewater goby habitat encompasses approximately 9 to 12 hectares (22.5 to 36 acres). About 75 percent of this locality is within the Sonoma Beach State Park and the rest is privately owned. The sand spit was closed during all sampling.

Cheney Gulch – Cheney Gulch drains into a salt marsh that in turn drains to Bodega Bay. The available tidewater goby habitat encompasses around 2 to 5 hectares (5 to 10 acres). About 90 percent of this locality occurs in Doran County Park and the rest is privately owned. Tidewater gobies were last recorded here in 1948. All sample sites for this study were within the salt marsh. At the time of sampling, little fresh water flowed into this salt marsh and the marsh had a muted tidal influence.

Marin County:
Estero Americano – This site is bisected by the Sonoma/Marin County line. The available tidewater goby habitat encompasses approximately 300 to 400 hectares (750 to 1,000 acres). All of the adjacent lands are privately owned. The sandbar at this location was not completely closed and the estuary was partially tidal at the time of sampling.

Estero de San Antonio - The available tidewater goby habitat encompasses approximately 200 to 300 hectares (500 to 750 acres). All of the adjacent lands are privately owned. The sandbar at this location was not completely closed and the estuary was partially tidal at the time of sampling.

Walker Creek - The available tidewater goby habitat encompasses approximately 10 to 20 hectares (25 to 50 acres). All of the adjacent lands are privately owned. The only recorded collection of tidewater gobies at Walker Creek occurred in 1897. A sandbar was not present and the estuary was completely tidal at the time of sampling for this study.

Lagunitas Creek - The available tidewater goby habitat encompasses approximately 10 to 20 hectares (25 to 50 acres). All of the adjacent lands are privately owned. Tidewater gobies were last collected here in 1953. Sampling was not conducted on the lee side of levees. A sandbar was not present and the estuary was completely tidal at the time of sampling.

Rodeo Lagoon - The available tidewater goby habitat encompasses approximately 15 to 20 hectares (37.5 to 50 acres) and is located entirely within the Golden Gate National Recreation Area. The National Park Service was conducting sampling at this particular location in 1996 and had established sample sites throughout the lagoon. I assisted the Park Service and incorporated water quality sampling at their sample sites. The sand spit was closed during all sampling.

Methods

Site selection

For convention, *site* in this report refers to sample sites or sample stations within a water body, and *location* refers to water body. At each location I dispersed up to ten sample sites around the shoreline of the lagoon or estuary. Sample sites within locations were not randomly selected. Sites conducive to seining were selected whenever possible (i.e. no more than about 1 m deep and free of major obstructions) as my primary fish collection gear was a beach seine. Sample sites were dispersed within each location to capture the variability of water quality present within the water body. Where I could not locate seine sites dispersed throughout the water body, sites were selected for dip-net or otter trawl sampling. Latitude and longitude were recorded at each site. Coordinates were determined using a Garmin GPS 45 handheld global positioning system (GPS) receiver accurate to within 100 m radius.

Water Quality Measurement

Water quality parameters were measured at each sample site before fish collection in undisturbed water as similar as possible to the habitat to be sampled for fish. Care was taken not to influence fish collection samples by alarming fish into or out of the intended path of the sample gear.

Water quality was measured at a depth near or equal to the maximum depth at which the gear would be fished. Measurements were collected only near the surface of the water column at the first few sites sampled, but a more rigorous protocol was implemented thereafter, that required measurements be collected near the near the water surface and the bottom just above the substrate. Near-surface water quality measurements were collected within 30 cm from the top of the water column (enough to submerge the probes of the various instruments used), and bottom measurements were collected within 20 cm of the substrate. At very shallow sites (30 cm and less) measurements were taken at mid-depth and water quality was assumed to be homogenous from top to bottom; subsequent analyses treated them as such.

Salinity in parts per thousand (ppt) and water temperature in degrees centigrade (ºC) were measured using a Yellow Spring International (YSI) Model 30 salinity/conductivity/temperature meter. Dissolved oxygen (DO) concentration, recorded as milligrams per liter (mg/l), was measured with a YSI Model 51B dissolved oxygen meter. The dissolved oxygen meter was calibrated daily using the air calibration method (YSI instruction manual). An Oakton WD-35615-Series pH/mV/temperature meter was used to measure pH and was calibrated daily against a 7.0 buffer solution. Turbidity was assessed by opening an empty jar 10-30 cm under the water surface, transferring a sample to a specimen jar, and immediately measuring turbidity in nephelometric turbidity units (NTU's) to the nearest whole NTU using a HF Scientific DRT-15CE portable turbidimeter.

Physical Habitat Classification

Minimum and maximum depths were recorded for each tidewater goby sample set. For the beach seine and otter trawl sets, depths were measured with a staff rod marked in 0.1 foot increments and recorded depths were later converted to centimeters. Otter trawls depths were determined from one to several point measurements of depth along the length of the trawl set. For dip net sets, each dip-netter estimated the maximum and minimum depths that he/she sampled over their respective set.

Dominant and subdominant substrates were recorded at each sample site (Table 2). In instances where the subdominant substrate was estimated to be an insignificant component (i.e. a sandy beach with few stones on it), the subdominant substrate was classified as “None”. Dominant and subdominant vegetation types were also recorded (Table 3).

Table 2. Substrate types used in visual classification.

Substrate	Description
Rock	Minimum diameter estimated greater than 50 mm
Gravel	Minimum diameter estimated 5 to 50 mm
Sand	Minimum diameter estimated 0.125 to 5 mm
Mud	Minimum diameter estimated less than 0.125 mm
Muck	Mixture of mud and decomposing organic material, often anoxic and accompanied by the smell of hydrogen sulfide when disturbed
Organic	In some cases the substrate was obscured by dense mats of grass and roots
Other	Substrate types rarely encountered were noted and given this classification
None	Recorded only as the subdominant substrate when the dominant substrate completely characterized substrate of the sample site

Table 3. Vegetation types used in visual classification.

Vegetation type	Description
Bare substrate	Substrate not covered by any macrophytes or filamentous algae
Filamentous algae	Filamentous algae
Free vascular	Vascular vegetation free floating
Rooted vascular	Vascular vegetation not free-floating
Flooded terrestrial	Terrestrial grasses or shrubs in flooded portions of lagoon or estuary
Other	Vegetation types rarely encountered were noted and given this classification
None	Recorded as the subdominant vegetation type in instances where there was no significant contribution made by any subdominant vegetation type

Fish Collection

Whenever conditions allowed, a 3 m long by 1.2 m deep beach seine with 3.2 mm mesh and a heavy leadline was employed. Set lengths were measured and varied depending on local conditions. Water depth, vegetation, and density of fish all influenced the practical length of seine sets. Two seine sets were usually performed at each site, adjacent to where water quality was measured. Density of tidewater gobies was reported as the number of individuals captured per meter of set length (combined set length where two sets were performed).

Long-handled dip nets (40.6 cm by 30.4 cm frame with 1.6 mm mesh) were used to sample fish at sites that could not be effectively seined because of their small area or heavy vegetation. Two crew members netted adjacent but independent areas for a 25 minute period at each site. Dip net results were not used to calculate fish density.

A small tow net (2.1 m by 1.1m with mesh size less than 1 mm) modified into an otter trawl was employed at some sampling sites in Humboldt Bay where muddy bottom and/or depth made wading conditions impractical for seining. When towed, 25.4 by 30.5 cm otter boards forced the net to open and skid along the bottom. Trawl set lengths were visually estimated.

Fish were identified to species and enumerated. Up to 30 individuals of each species captured in a location visit were measured for length. Standard length was used for all goby species measured. All fish were released at the capture site, except for occasional fish retained for voucher purposes. Vouchered specimens were transferred to the Humboldt State University fish museum collection.

Tidal connectivity

Though not considered a priori as part of this study, it became apparent after visiting multiple locations that positive detections of tidewater goby occurred more frequently in water bodies with little salinity gradient and limited connectivity to tidal influence. Post-sampling, I parsed the locations I visited into four subjective categories based on observation of marine connectivity at the time of sampling. These categories were: "fully tidal" (no complete sandbar closure and subject to full tidal influence at time of sample); "partial" (some form of incomplete tidal impediment at time of sample that resulted in a muted tidal influence at most); "seasonal closure" (full sandbar closure and no tidal influence at time of sample); and "severed" (tidal influence completely severed — Freshwater Lagoon was the only instance of this). For this analysis, those locations in Humboldt Bay formerly lumped into bigger environs were separated (Jacoby Creek and Klopp Lake for instance were not lumped into "Arcata Marsh and environs").

Data analysis

For those water bodies where tidewater gobies were captured by seining, the relationship of tidewater goby density (number per meter of seine set length) at each sample site to various water quality parameters was explored using a generalized linear model (McCullagh and Nelder 1989) and analysis of covariance with location as a grouping factor (model: $\log_{10}(\text{density}+1) = \text{location} + \text{water quality parameter}$). Density was log transformed after adding 1.0 because of zeros in the data. Only densities estimated by seine sampling were used in the analysis because tidewater gobies were not captured in the trawl and sample area estimates were not attempted for dip-net sets.

A Fisher's exact test (Fisher 1922) was used to test for independence in the distributions of dominant substrate and vegetation between water bodies where tidewater goby were and were not detected. The Fisher's exact test was also used to compare dominant substrate and vegetation distributions between sample sites where tidewater goby were and were not found within a water body for water bodies that sampled positive for tidewater goby presence.

1997 site re-visits

In 1997, I initially re-sampled eight locations to confirm that tidewater goby were still detectable, and then selected Lake Earl, Stone Lagoon, Big Lagoon, and Estero Americano for repeated visits. Each of the subsequent visits consisted of sampling the same six-to-eight sites twice within two days. The sites at each water body were sampled in random order on first replicate of each visit, and the order was reversed for the second replicate of the visit except for Estero Americano where the length of the water body made random order of site visit impractical. Three such replicated visits were made to Lake Earl, and two to the others. Consistency of tidewater goby detection and variability in water quality measurements between replicates and between visits were assessed.

Results

Tidewater goby were detected with beach seine and/or dip-net in 12 of the 20 water bodies sampled in 1996 (Table 4). Tidewater goby were again detected at all of the locations revisited in 1997 (n = 8). The modified otter trawl was only employed within the fully tidal waters of Humboldt Bay at Mad River Slough, Freshwater Slough, and Faye Slough where no tidewater goby were captured.

The highest densities of tidewater gobies were captured at Rodeo Lagoon where in one 3 m seine haul over 1,500 tidewater goby were captured (mean = 100.3 per meter of seine set length, range 6.9 to 514.1/m). Water quality conditions were anoxic with several dissolved oxygen measurements of less than 1.0 mg/l recorded. A fish kill of prickly sculpin *Cottus asper* and three-spine stickleback *Gasterosteus aculeatus* occurred immediately prior to sampling at Rodeo Lagoon, which may have still been in progress (Fong 1997a, 1997b) during my sample collections. Fish densities were potentially elevated along the margins of the lagoon because of the extremely low oxygen levels, but the tidewater gobies appeared robust and less than 1% mortality was observed while handling.

Table 4. Locations where tidewater goby were and were not detected in 1996.

Detected	Not detected
Tillas Slough	Redwood Creek
Lake Earl[1]	Freshwater Lagoon
Stone Lagoon[1]	Mad River Slough[2]
Big Lagoon[1]	Freshwater Slough[2]
Arcata Marsh[2] (only at Jacoby Creek this study)	Brush Creek
Ten Mile River[1]	Cheney Gulch
Pudding Creek	Walker Creek
Davis Lake[1]	Lagunitas Creek[2]
Salmon Creek[1]	
Estero Americano[1]	
Estero de San Antonio[1]	
Rodeo Lagoon	

[1] Locations revisited in 1997. Presence was reconfirmed at all revisited locations.

[2] Tidewater goby have since been detected adjacent to these waters on the lee side of levees where no sample occurred for this study.

Densities of tidewater goby at locations where they were found were highly variable. Rodeo Lagoon was the only location where tidewater goby were captured at every sample site. Most locations had one to several sites with no capture. Big and Stone Lagoons each had low densities of tidewater gobies. Three of 10 sites detected positive at Big Lagoon (with densities of 0.73, 0.11, and 0.07 gobies/m of seine set length), and 5 of 10 sites detected positive at Stone Lagoon (mean density of 0.09/mof seine set length, range 0.06 to 0.58).

Water Quality

Habitats utilized by tidewater goby across the range surveyed were highly variable (Figure A-1 through Figure A-18 in Appendix A). At the extremes of water quality measured near the substrate, tidewater goby were found in salinities that included fresh 0.1 and hypersaline 37.8 ppt water, concentrations of dissolved oxygen at 0.2 to 15.5 mg/l, and temperatures between13.0 -25.4 ºC.

Strong location effects overwhelmed relationships between salinity and tidewater goby density Figure 2 and Figure 3. Tests of tidewater goby density against each of the water quality parameters yielded no results significant at $\alpha = 0.05$ (Table 5). Surface salinity was not useful for explaining tidewater goby density ($p = 0.55$). Likewise, no significant relationship was revealed between density and bottom salinity or any of the other water quality parameters top or bottom (Table 5).

Though salinity was highly variable between water bodies where tidewater goby were detected ranging from a mean of 1.8 ppt surface salinity at Davis Lake in 1996 (standard deviation = 1.19) to 32.2 ppt during the October 2 trip to Estero Americano in 1997 (standard deviation = 4.48), it was relatively homogeneous within those water bodies with the exceptions of Big Lagoon and Ten Mile River Figure A-1). Big Lagoon's variation can be explained by the location of two sites upstream of Highway 101 bridge over the inlet (with salinities of 0.1 and 1.0 ppt) and one in a marshy area adjacent to the main body (salinity 8.5 ppt) where the water was far less saline than the main body of the lagoon. The main body of Big Lagoon where most of the gobies were found was fairly homogonous with a mean surface salinity of 25.4 ppt over 7 sites (standard deviation = 2.71). Ten Mile River exhibited a gradient of salinity with highly marine water near its mouth (29.6 ppt surface), strong stratification of saline and fresh water, and fresh water at the estuary's inland source (0.1 ppt). Variability in salinity at Ten Mile River was among the highest of locations where tidewater goby were detected (standard deviation =11.6).

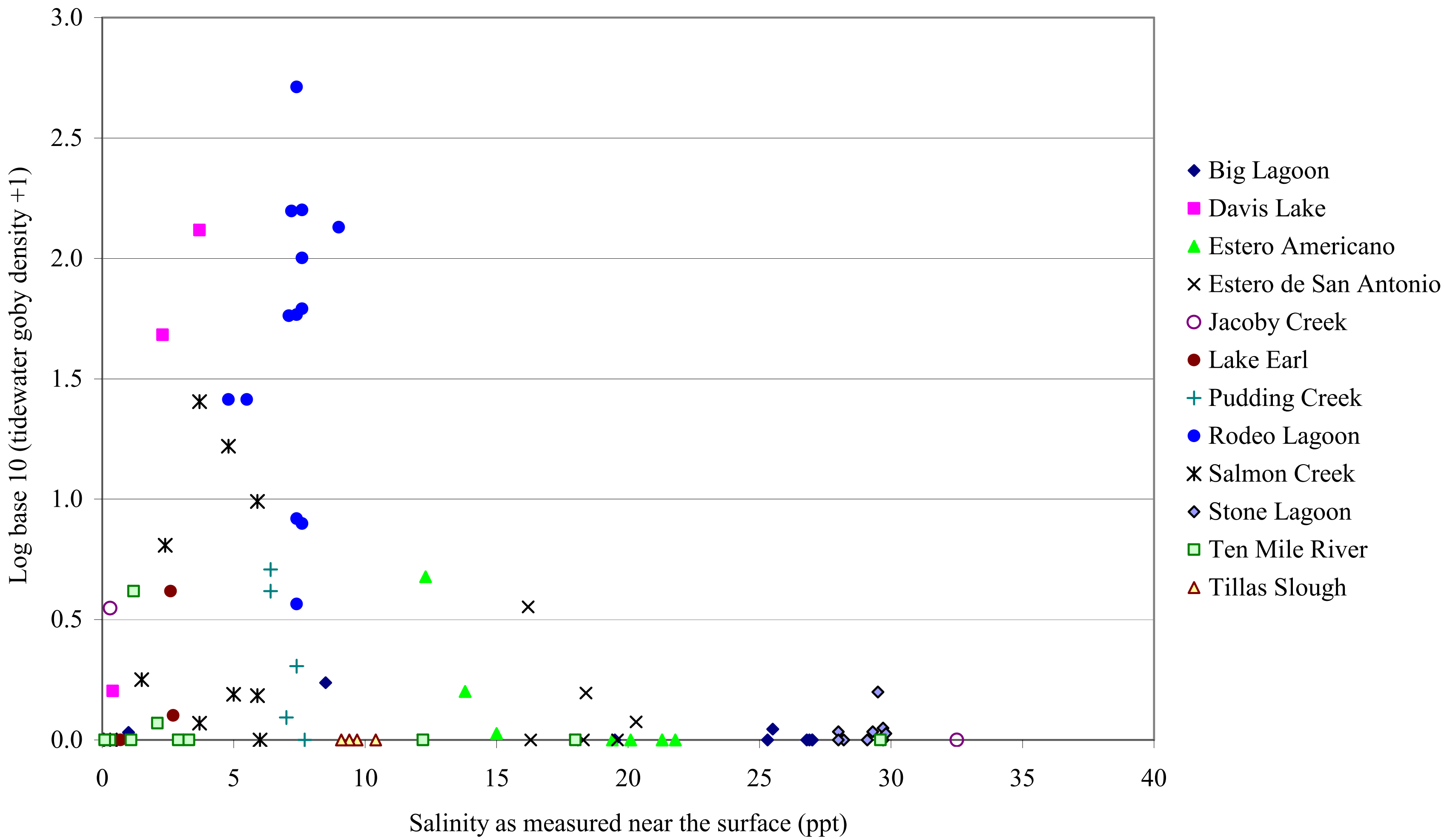

Figure 2. Tidewater goby density for 1996 seine samples transformed by Log_{10} (density + 1) and plotted against surface salinity.

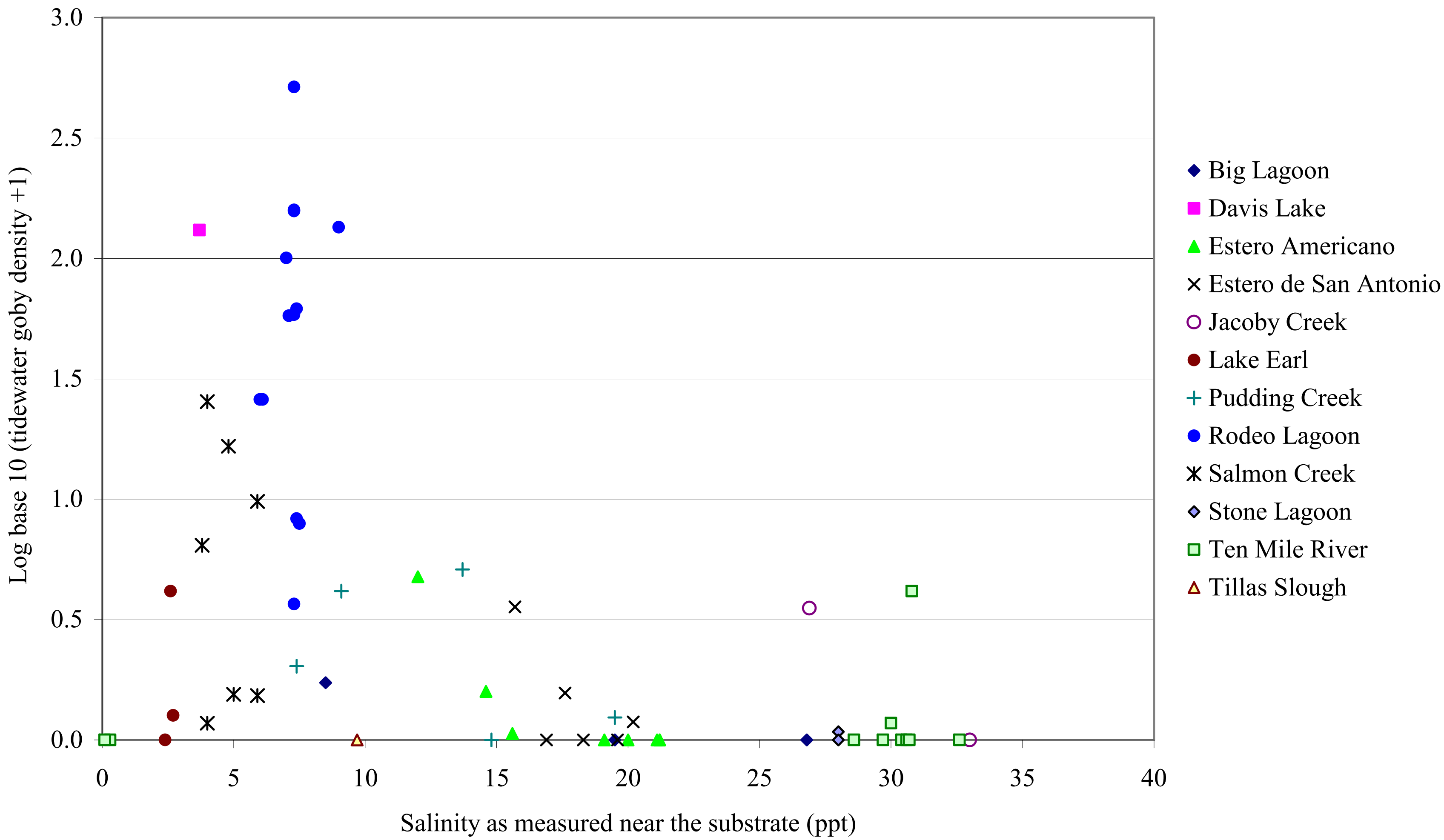

Figure 3. Tidewater goby density for 1996 seine samples transformed by Log_{10} (density + 1) and plotted against bottom salinity.

Table 5. Results of generalized linear modeling and analysis of covariance on relationship of water quality parameters to log-transformed tidewater goby density for all water bodies where the species was detected by seining in 1996.

Parameter	Near surface		Near substrate	
	r^2	p	r^2	p
Salinity	0.69	0.55	0.76	0.65
Temperature	0.69	0.51	0.76	0.76
pH[1]	0.30	0.45	0.18	0.44
Dissolved Oxygen	0.75	0.63	0.74	0.87
Turbidity	0.79	0.78	Not measured	

[1] Because of missing values at the other locations, pH analysis limited to Estero de San Antonio, Jacoby Creek, Salmon Creek, and Ten Mile River

Physical Habitat

Physical habitat conditions where tidewater goby were detected were also highly variable. Positive detections were made over a wide range of available substrates from anoxic muck and mud to rock, and in habitats ranging from those void of vegetation to those with emergent aquatic vegetation so thick that even dip-net sampling was a challenge.

Among 1996 sample sites in those water bodies where tidewater goby presence was confirmed, bare substrate was the dominant vegetation type in 25 of 43 (58%), followed by filamentous algae (30%) and rooted vascular (12%). The incidence of bare substrate was even higher at 83% (34 of 41) for those sites where tidewater goby were not found, followed by filamentous algae (15%) and rooted vascular (3%). However, the sampled vegetation type distributions were not significantly different between water bodies with and without tidewater goby detection (Fisher's exact test; $p = 0.27$), or among “present” and “absent” sample sites within water bodies where tidewater gobies were found (Fisher's exact test; $p = 0.06$).

Sand and mud were the most frequent dominant substrates recorded across all 1996 samples (40% and 36% respectively). Sand was observed at a slightly higher frequency at locations where tidewater goby were found (44% vs. 33%), but differences in dominant substrate distributions were not significant between waters with and without tidewater goby detection (Fisher's exact test, $p = 0.30$). Dominant substrate classifications also did not differ significantly among “present” and “absent” sample sites within water bodies where tidewater gobies were detected (Fisher’s exact test; $p = 0.56$).

The frequency distribution of sampled substrate and vegetation types should not be considered representative of the distribution of these variables in the available habitats. Sample sites were selected, in part, based on their suitability to be fished with a beach seine. Sample sites typically occurred near the shoreline of water bodies because potential sites away from shore were usually too deep to wade and not appropriate for the gear employed. Many locations had thickets of vegetation along their shorelines that may have harbored tidewater goby but were too dense to sample.

Compare 1996 to 1997

Salinities measured at Lake Earl in 1997 were very similar to those observed in 1996 (Figure 4) and were among the lowest recorded over the study (Figure A-1 through Figure A-4 in Appendix A). Except for higher variation at Big Lagoon, salinities at Stone and Big Lagoon were roughly similar to each other, but both were much less saline in 1997 than in 1996 (Figure 5 and Figure 6). These lagoons are within a few km of each other and experience similar hydrologic conditions.

In July, 1997 salinities in Estero Americano were similar to those measured in October 1996, but increased over the course of summer and early fall (Figure 7). By late summer 1997, there were no visible surface sources of fresh water flowing into this long narrow estuary. The upper end of Estero Americano experienced sunny conditions on nearly every visit, while the lower end remained shrouded in a marine layer of fog. This contributed to an evaporation-pond like condition in 1997, whereby the upper end of the estuary (where tidewater goby were consistently found) became hyper-saline toward the end of this survey, while the estuary near its mouth remained marine.

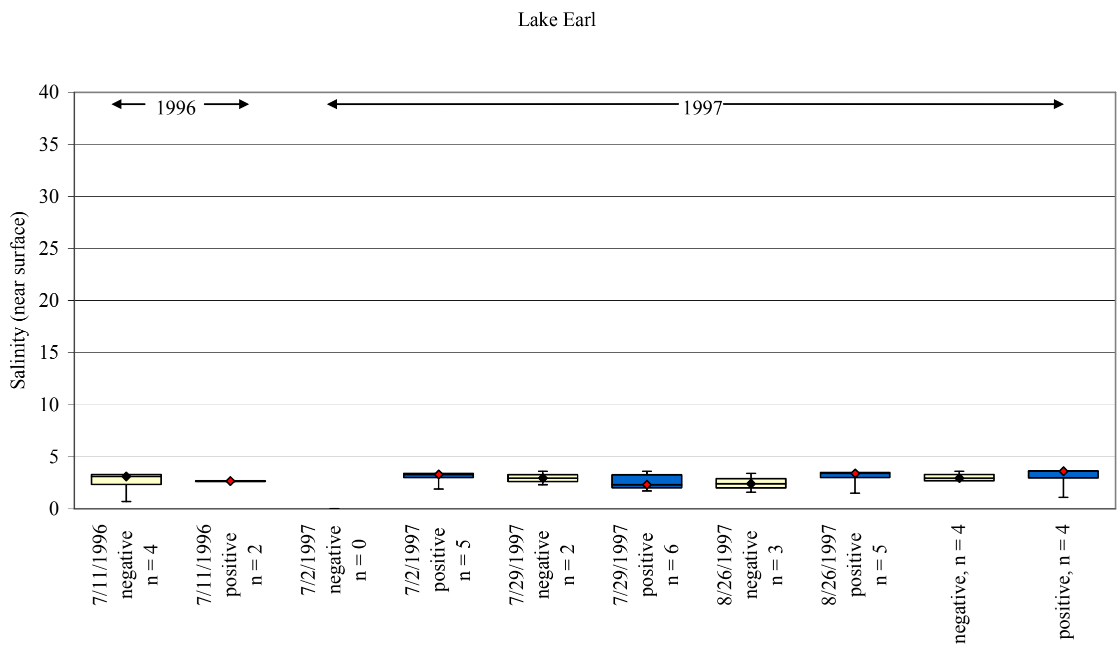

Figure 4. Lake Earl salinity as measured near the surface for all visits 1996 and 1997; sample sites positive and negative for tidewater goby detection are presented side-by-side.

Stone Lagoon

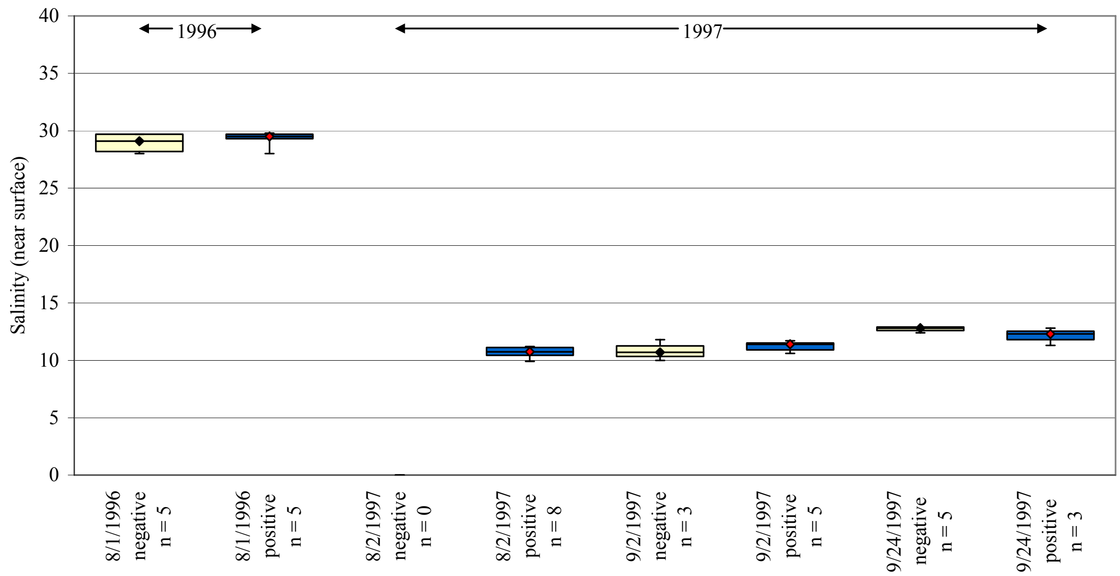

Figure 5. Stone Lagoon salinity as measured near the surface for all visits 1996 and 1997; sample sites positive and negative for tidewater goby detection are presented side-by-side.

Big Lagoon

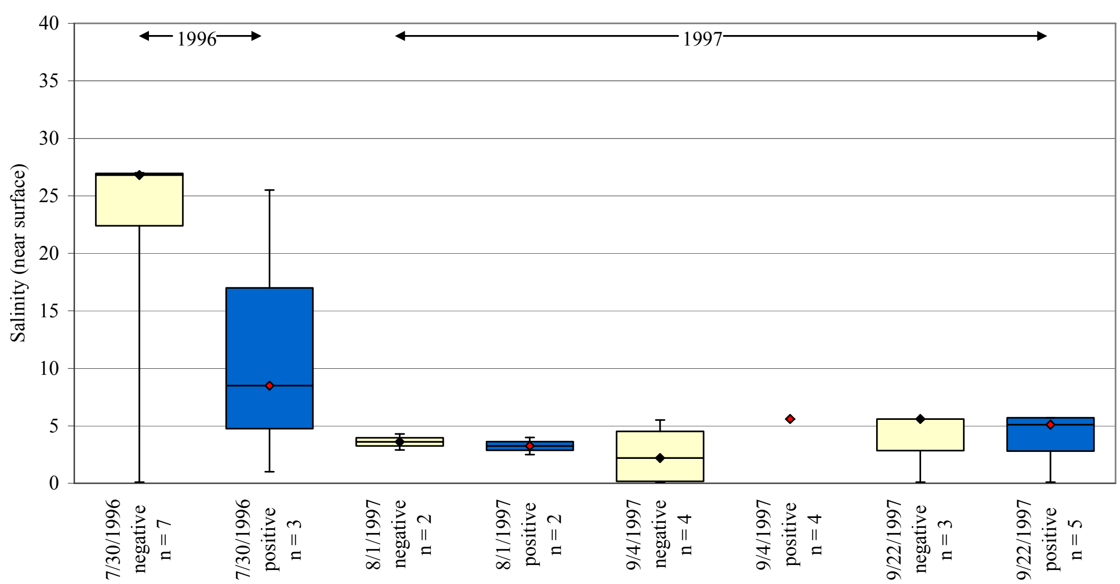

Figure 6. Big Lagoon salinity as measured near the surface for all visits 1996 and 1997; sample sites positive and negative for tidewater goby detection are presented side-by-side.

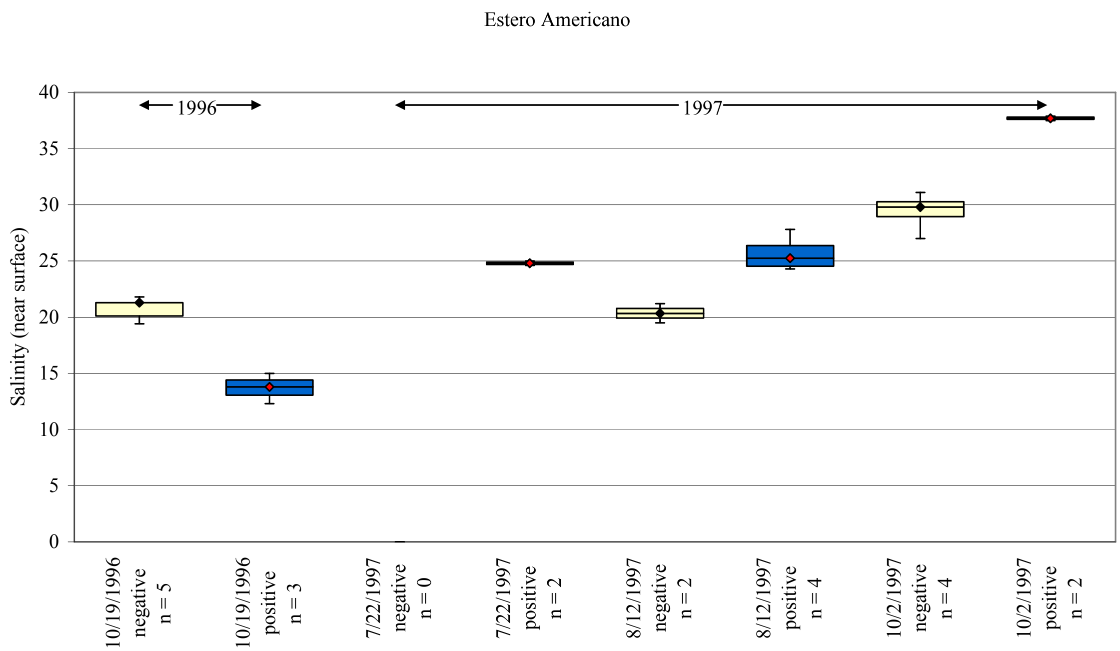

Figure 7. Estero Americano salinity as measured near the surface for all visits 1996 and 1997; sample sites positive and negative for tidewater goby detection are presented side-by-side.

Tidewater goby were detected during each visit to all of the four water bodies repeatedly visited in 1997. At Lake Earl and Stone Lagoon, tidewater goby were detected at least once at all sites (Table 6). Only one site at Big Lagoon never sampled positive for tidewater goby (Site 6); this site was located on the sandbar where the lagoon frequently breaks open to the ocean during winter storms. The site nearest the breach at Estero Americano (Site D) never sampled positive, nor did the next nearest site 2 km inland (Site D). In fact, the closest site to the breach where tidewater gobies were captured was approximately 5.2 km inland (Site B). Tidewater goby were occasionally found at a site immediately adjacent to the breach site at Stone Lagoon (Site 3) and were captured frequently at the sample site located near the breach in Lake Earl (Site 1).

Table 6. Density of tidewater goby (number/m of seine set length) in samples collected 1997. Shaded cells indicate inconsistent detection/non-detection between replicate samples. "ns" = no sample. Boxes indicate inconsistent detection/non-detection between replicate visits.

Location		Visit 1	Visit 2		Visit 3		Visit 4	
		Sample 1	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
Lake Earl	Site	7/2	7/29 to 7/30		8/26 to 8/28		9/10 to 9/12	
	1	0.30	3.35	Ns	7.28	9.55	10.61	11.01
	2	1.50	0.00	Ns	3.69	2.76	1.92	0.80
	3	0.14	0.15	ns	0.00	0.00	0.00	0.10
	4	41.60	0.07	ns	0.04	0.14	0.00	0.10
	5	0.76	0.15	ns	ns	ns	ns	ns
	5A	ns	ns	ns	10.00	52.00	13.33	13.00
	6	ns	0.00	ns	0.00	0.00	0.00	0.06
	7	ns	6.08	ns	1.29	1.06	2.66	4.18
	8	ns	0.14	ns	0.00	0.00	0.00	0.00
Big Lagoon	Site	8/1	9/4to 9/6		9/22to 9/23			
	1	2.41	1.64	0.67	0.66	0.55		
	2	1.37	0.00	0.70	0.12	0.10		
	3	0.00	0.09	0.03	0.07	0.07		
	4	0.00	0.06	0.03	0.00	0.08		
	5	ns	0.00	0.00	0.15	0.08		
	6	ns	0.00	0.00	0.00	0.00		
	7	ns	3.40	3.42	1.08	0.81		
	8	ns	0.00	0.00	0.00	0.10		
Stone Lagoon	Site	8/2 - 8/6	9/2to 9/3		9/24to 9/25			
	1	0.76	0.00	0.00	0.00	0.00		
	2	0.28	0.14	0.07	0.07	0.00		
	3	0.69	0.00	0.05	0.00	0.00		
	4	2.28	0.87	0.46	4.13	1.91		
	5	0.37	0.00	0.98	0.00	0.00		
	6	3.44	0.08	0.00	0.47	0.07		
	7	0.13	0.04	0.03	0.00	0.00		
	8	0.34	0.05	0.05	0.00	0.00		
Estero Americano	Site	7/22	8/12 to 8/14		10/2 to 10/3			
	A	0.08	0.28	0.53	0.00	0.00		
	B	ns	0.06	0.00	0.00	0.00		
	C	ns	0.00	0.00	0.00	0.00		
	D	ns	0.00	0.00	0.00	0.00		
	E	0.73	1.17	0.73	1.25	ns		
	F	ns	2.41	2.55	6.00	ns		

Measurements of salinity were similar between replicate site samples for all four locations (Table 7). With the exception of Estero Americano, salinity was also relatively consistent between visits (Table 7 and Figure 7). As stated earlier, Estero Americano experienced an increase in salinity in its upper portion over the course of summer due to evaporation and lack of freshwater inflow.

Nearly all of the other water quality parameters exhibited little variation over the course of this study. However, dissolved oxygen was highly variable between replicates at times (Table 8). Dissolved oxygen readings tended to be lowest during morning and highest during afternoon hours when photosynthesis infused the water with oxygen. Because sites were visited in a particular order for the first replicate then in reverse order for the second replicate, replicate measurements were often made at differing times of day.

Table 7. Surface salinity measurements collected in 1997. "ns" = no sample.

Location		Visit 1	Visit 2		Visit 3		Visit 4	
		Sample 1	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
Lake Earl	Site	7/2	7/29 to 7/30		8/26 to 8/28		9/10 to 9/12	
	1	3.4	3.6	ns	3.5	2.6	3.6	3.6
	2	3.4	3.6	ns	3.5	2.9	3.7	2.6
	3	3.3	3.5	ns	3.4	2.5	3.6	2.7
	4	3.0	2.5	ns	3.0	2.5	3.2	2.4
	5	1.9	1.7	ns	ns	ns	ns	ns
	5A	ns	ns	ns	1.5	1.3	1.1	2.1
	6	ns	2.3	ns	2.4	2.3	2.7	2.1
	7	ns	2.1	ns	3.4	3.4	3.6	3.7
	8	ns	2.0	ns	1.6	1.4	2.7	2.0
Big Lagoon	Site	8/1	9/4to 9/6		9/22to 9/23			
	1	2.5	5.6	5.6	5.1	5.7		
	2	4.0	4.2	4.2	2.8	2.9		
	3	2.9	5.6	5.7	5.7	5.7		
	4	4.3	5.6	5.6	5.6	5.7		
	5	ns	0.1	0.1	0.1	0.1		
	6	ns	5.5	5.7	5.6	5.8		
	7	ns	5.6	5.6	5.7	5.7		
	8	ns	0.2	0.2	0.1	0.1		
Stone Lagoon	Site	8/2 - 8/6	9/2to 9/3		9/24to 9/25			
	1	9.9	10.0	12.2	12.6	13.3		
	2	10.2	11.4	11.5	11.3	13.4		
	3	10.6	11.8	11.5	12.4	13.3		
	4	10.9	11.7	11.4	12.3	13.0		
	5	10.5	10.7	11.5	12.9	13.4		
	6	11.1	11.5	11.6	12.8	13.2		
	7	11.2	10.6	11.5	12.8	13.2		
	8	11.2	10.9	11.5	12.9	13.2		
Estero Americano	Site	7/22	8/12 to 8/14		10/2 to 10/3			
	A	24.6	24.3	23.5	30.0	35.1		
	B	ns	24.6	22.4	29.6	34.6		
	C	ns	21.2	17.9	27.0	28.2		
	D	ns	19.5	17.3	31.1	27.4		
	E	25.0	27.8	23.6	37.5	ns		
	F	ns	25.9	21.4	37.9	ns		

Table 8. Dissolved oxygen measurements collected near water's surface in 1997. "ns" = no sample; "NA" = not measured.

Location		Visit 1 Sample 1	Visit 2 Sample 1	Visit 2 Sample 2	Visit 3 Sample 1	Visit 3 Sample 2	Visit 4 Sample 1	Visit 4 Sample 2
Lake Earl	Site	7/2	7/29 to 7/30		8/26 to 8/28		9/10 to 9/12	
	1	0.0	9.5	ns	9.0	9.0	10.1	10.2
	2	0.0	8.5	ns	8.7	6.6	6.9	3.5
	3	0.0	11.3	ns	11.3	10.9	12.7	8.1
	4	8.7	2.8	ns	15.5	5.6	14.3	7.5
	5	8.9	4.2	ns	ns	ns	ns	ns
	5A	ns	ns	ns	10.0	12.6		8.3
	6	ns	7.9	ns	11.3	9.1	11.8	8.1
	7	ns	8.7	ns	9.6	12.1	12.0	10.2
	8	ns	10.2	ns	8.6	11.0	15.0	3.1
Big Lagoon	Site	8/1	9/4to 9/6		9/22to 9/23			
	1	8.8	8.2	9.4	8.3	7.5		
	2	9.2	8.2	9.1	10.8	8.9		
	3	9.7	9.6	NA	9.5	7.6		
	4	9.0	9.0	9.1	8.9	8.0		
	5	ns	8.5	9.3	7.2	7.9		
	6	ns	8.9	NA	8.7	7.5		
	7	ns	8.5	9.2	10.1	6.6		
	8	ns	9.3	7.0	9.8	9.1		
Stone Lagoon	Site	8/2 - 8/6	9/2to 9/3		9/24to 9/25			
	1	8.1	8.7	NA	8.5	7.5		
	2	8.0	10.3	NA	7.3	8.4		
	3	7.3	10.0	NA	7.6	8.0		
	4	8.5	10.1	NA	6.7	7.0		
	5	7.4	8.1	NA	8.3	7.0		
	6	8.1	9.1	NA	8.2	6.9		
	7	8.7	8.4	NA	8.0	7.5		
	8	8.1	9.0	NA	8.9	7.4		
Estero Americano	Site	7/22	8/12 to 8/14		10/2 to 10/3			
	A	8.1	6.2	12.0	8.8	9.0		
	B	ns	7.1	10.6	8.6	11.4		
	C	ns	7.2	6.0	9.2	9.1		
	D	ns	9.6	9.3	8.3	8.8		
	E	0.0	15.2	8.6	6.5	ns		
	F	ns	13.7	7.1	2.6	ns		

Tidal connectivity

Tidewater goby were not detected in any of the seven fully tidal waters sampled (Table 9). Tidewater gobies were also not detected in Freshwater Lagoon, which has had no connectivity to tidal influence since construction of U.S. Highway 101 on its sandbar, and where the last documented record of the species dates back to 1951. Tidewater goby were detected in 12 of the 17 waters with partial or full seasonal closure.

Table 9 Tidal connectivity and tidewater goby presence in 1996. The multiple locations that comprised "Arcata Marsh and environs" elsewhere in this study are treated separately here.

Connectivity of water body to marine sources	Locations sampled	Positive for tidewater goby	Proportion
Fully tidal	6	0	0
Partial	9	5	0.556
Seasonal closure	8	7	0.875
Severed	1	0	0

Discussion

The goal of this study was to measure habitat and water quality conditions coincident with collection of tidewater goby presence and abundance data to identify parameters having the most influence on distribution of the species in northern California. Results of this study are intended to refine the existing literature. Given its emphasis in the literature on tidewater goby, I expected salinity to have a greater influence on tidewater goby distribution than any of the other parameters sampled. In this study however, tidewater gobies were most abundant in lagoons/estuaries without a tidal influence at the time of sample and with relatively homogenous water quality between sample sites, regardless of salinity or other water quality conditions encountered. Tidewater goby were found in low abundance or were absent in estuaries where the mouth was frequently open to the ocean. Some populations appeared to be flourishing under conditions well outside those reported elsewhere as "optimal" for tidewater goby, such as salinities much higher than 10 ppt, and extremely low dissolved oxygen concentrations. Reported habitat preferences for tidewater goby in much of the existing literature may simply reflect common water quality and habitat parameters found in waters that provide physical refuge for sensitive life histories of the species.

In their larval stage, tidewater gobies are pelagic and are therefore more susceptible to entrainment in waters ebbing out of a habitat than would the later benthic-oriented life histories of the species. Large lagoons, in addition to often having a closed sandbar for most of the year, exhibit a low turnover of water with each tide when they're open by virtue of their enormity relative to their mouths, and provide vast areas of refuge from entrainment in ebbing waters. Marshes with only partial or intermittent connection to tidal influence can also provide critical refuge from entrainment. Sandbar formation at many lagoons and estuaries frequently severs connection with tidal influences, often for many months.

A potential explanation for many of the observations of low salinity (<10 ppt) across the range of tidewater goby distribution may be reflective of a correlation between salinity and connectivity to marine-source waters. Salinity is a moderate correlate for tidal connectivity, a feature which may be far more important for explaining tidewater goby distribution than individual physical habitat or water quality parameters. Estuaries and lagoons with partial or full temporary isolation from the marine environment are more likely to exhibit low salinities during tidally restricted periods than those that are fully tidal, largely due to freshwater inflow. Water bodies fully connected to tidal influence are logically going to be marine oriented, except during periods of high freshwater runoff. However, tidewater goby have been shown to tolerate even hyper-saline water (Swift et al. 1989; Worcester and Lea 1996), and I found them in the hypersaline waters of Estero Americano in 1997 where tidal exchange and freshwater inflow were both very low. Much of the existing tidewater goby literature has suggested a preference for low salinities, but the correlation between salinity and tidal connectivity has largely been ignored. I suggest that high salinity in an open estuary is not the causative factor that inhibits tidewater goby distribution, but rather the exchange of water on a sub-daily basis that both winnows pelagic larvae out of the system and reduces prey base; and that those systems with periodic isolation from tidal influence have a much higher likelihood of harboring tidewater goby regardless of salinity.

Successful spawning and subsequent recruitment to the benthic stage depends on a sequence of successful life-history transitions, all likely enhanced by some form of habitat stability. Successful spawning depends on the presence of suitable habitat that is not de-watered over a burrow construction period of 1 – 2 days (in a captive population; Swift et al. 1989), a courtship and mating period of 2 – 2.5 days (Swenson 1995), and an egg incubation period of 7 - 11 days (Swift et al. 1989; Swenson 1995; Capelli 1997). After hatch, recruitment of larvae to the benthic life history requires subsequent refuge from entrainment out of the water body for a period lasting as long as a couple weeks or more. Limited information exists on the duration of the pelagic larval stage of tidewater goby. Observation of eggs and subsequent larvae in an aquarium suggests that this period can last from a few days to a couple of weeks (Camm Swift, personal communication). Dawson et al. (2002) speculate that the larval period of tidewater goby is likely less than one month based on the species' similarities with the arrow goby *Clevelandia ios*; a phylogeographic sister species.

In recent sampling around Humboldt Bay, the Arcata Fish and Wildlife Office has discovered tidewater goby in "perched" off-channel habitats (unpublished data). These habitats are reached by very high tides, but are discontinuous with the bay for extended periods and potentially afford larval goby periodic opportunity to mature to benthic stage without exposure to entrainment. There are likely other benefits to tidewater goby from these off-channel habitats such as refuge from predation and increased food availability (Swenson 1995, 1999; Swenson and McCray 1996; Capelli 1997).

Some degree of isolation from marine influence and refuge for larval gobies from entrainment in ebbing tidal waters may be critical to reproductive success. However, complete isolation would hinder colonization and genetic infusion by gobies dispersed from other nearby source populations. Because tidewater goby are largely an annual species (Irwin and Soltz 1984; Swift et al. 1989; Swenson 1999), small pocket populations are especially vulnerable to occasional extirpation if for some reason all the cohorts of an age class fail to recruit to sexual maturity (habitat becomes dewatered, flood washes the animals out, eliminated by predation, etc). Small habitats in particular need occasional connectivity to other source populations for recruitment and recolonization. There exists a regime that includes both isolation and connectivity with the marine tidal environment that provides a suitable balance between entrainment loss and colonization/genetic exchange. The need for genetic exchange goes both ways - into the subpopulation and out to the metapopulation. Infrequent but occasional or low-level loss of individuals through entrainment contributes to genetic exchange and potential colonization of nearby habitats. These metapopulation dynamics are especially important to understand in a system like Humboldt Bay where tidewater goby are found in multiple but small dispersed habitats, and where a habitat's likelihood of occupancy may be greatly influenced by the presence and persistence nearby populations (Murphy et al. 1990; Moilanene and Nieminen 2002). The rate of genetic exchange between various Humboldt Bay populations is not yet completely understood. Further research into this question is crucial to effective management of habitat for these populations.

Encountering tidewater goby at a site does not necessarily indicate a self-sustaining population at that location. As discussed earlier, larval tidewater goby are pelagic and are particularly susceptible to entrainment. When lagoons breach, when off-channel habitats are flooded during storms, or when large tides alternately inundate and drain from perched marsh habitats, tidewater goby, especially larval stages, are likely entrained out of these sources and their potential to be deposited into non-source habitats is increased. It is possible that some of these habitats where the species is occasionally found are population sinks rather than viable production sites, though their contribution to either of these classifications is likely variable and dependent on local hydrology and tide.

Several miles of coastline exists between tidewater goby populations in portions of its range. Lafferty et al. (1999) documented probable recolonization in Honda Creek where the nearest potential source population based on prevailing longshore currents is 9 km to the north. In a genetic study of populations from Salmon River in Sonoma County to southern California, Dawson et al. (2001) found that genetic isolation along the coast was strongly correlated with absence of sandy substrate in intertidal zones. They propose that this correlation with substrate suggests dispersal is accomplished by benthic adults rather than pelagic larvae. The strength of this inference, however, may weaken within an embayment like Humboldt Bay where population exchange can occur within relatively protected and nearby waters. Pelagic larvae entrained out of source habitats but retained within a bay environment are more likely to reencounter suitable habitat on subsequent tides than those swept out of an estuary into open coastal waters (Gains and Bertness 1992).

With a few exceptions, sites I surveyed in Humboldt Bay were within tidal sloughs subject to full tidal influence — habitat where I never encountered tidewater goby. Roughly 85% of the former salt marsh habitat of Humboldt Bay has been lost to levee construction that began around the 1880’s (Barnhart et al. 1992). Water now ponds behind these levees in many locations with at least some muted connection to the fully tidal waters on the bay-side, usually through one or more of the numerous tide-gates located around the bay. Some of these lee-side waters have sampled positive for tidewater goby in recent years (Gannon Slough, Highway 101 ditch, small pond adjacent to Wood Creek on Freshwater Slough, small channels within Humboldt Bay National Wildlife Refuge, behind the levee of the Mad River Slough). Many of the lee-side waters around Humboldt Bay are on private land and very few have been sampled. A smaller scale but similar condition exists in the southern end of Tomales Bay at Lagunitas Creek where in 2003, tidewater goby were found in the lower portion of Tamasini Creek upstream of the tide gate that isolates it from the Lagunitas Creek estuary (Darrin Fong, personal communication).

Before alteration from levee and dike construction, an estimated 2,833 hectares of salt-marsh habitat fringed Humboldt Bay; now there are only 393 hectares (Monroe 1973, and Shapiro and Associates1980; as cited in Barnhart et al. 1992). These salt marshes likely featured numerous backwaters, oxbows from tributary streams, localized scour holes from large woody debris, and other characteristics that created habitat with intermittent or partial connection to tidal influence. Depressions and ponded waters “perched” at an elevation reached only occasionally by high tide provide key habitat features needed by tidewater goby and provide larval gobies refuge from entrainment.

Most of Humboldt Bay is no longer connected with its former salt marsh habitats, yet tidewater goby persist. As mentioned above, tidewater goby have been discovered behind tide gates of Humboldt Bay and Tomales Bay. Often the tributary behind the tide gate has been diked and the remaining channel is ditch-like. These tide gates mute, but do not completely eliminate, tidal connectivity. Even though these habitats are often highly channelized, strong daily water quality variability typical of a tidal environment is muted and the volume of water exchanged behind the tide gate with each tide is reduced. Larval gobies in these habitats may pass out to the bay at a rate slow enough that some reach benthic life history before being entrained.

In some locations behind Humboldt Bay tide gates, there are perched habitats that are reached only occasionally by the now muted tide (Figure 8). Very little sampling for tidewater goby has occurred around Humboldt Bay in channels or marshes behind the levees, but recent opportunities to survey these locations have resulted in discovery of the species in several formerly unknown sites. There are potentially numerous unknown but occupied locations around Humboldt Bay that support tidewater goby, both within drainage channels behind tide gates, and in perched off-channel habitats. The best opportunity to increase habitat for tidewater goby around Humboldt Bay may be creation of off-channel marshes or perched habitats. This could serve to alleviate concern over populations closely associated with tide gates when modifications to the gates are proposed for increased fish passage and geomorphic purposes.

Figure 8 Humboldt Bay "perched" habitats found to harbor tidewater goby. Waters adjacent to Gannon Slough (left) and Wood Creek on Freshwater Slough (right).

Habitat assessment

Rather than measure a suite of water quality and habitat parameters from a site to determine its suitability for tidewater goby, it may be far more informative to assess a site's potential to retain goby through their pelagic larval stage. Waters that occasionally connect with, but are periodically discontinuous from the tidal environment provide refuge for larval gobies as needed to make the life history transition to benthic juveniles. Though often found throughout estuaries, tidewater goby have been described to have a higher affinity for the upper end of bays and large estuaries (Swift et al. 1989; Capelli 1997). It's reasonable to suppose that individuals (especially larvae) at upper ends of these water bodies are less likely to be entrained out of the system. A metric (yet to be described) that depicts sandbar breaching regime, water exchange rate (from tidal or lotic sources), and frequency of connection to the marine may go well beyond habitat and water quality descriptors in explaining tidewater goby distribution. Restoration actions that consider refuge for the larval stage will likely be more effective than those that focus on achieving a water quality target for salinity or other variables.

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Appendices

Appendix A. Box plots of water quality parameters measured at all locations sampled for tidewater goby in 1996.

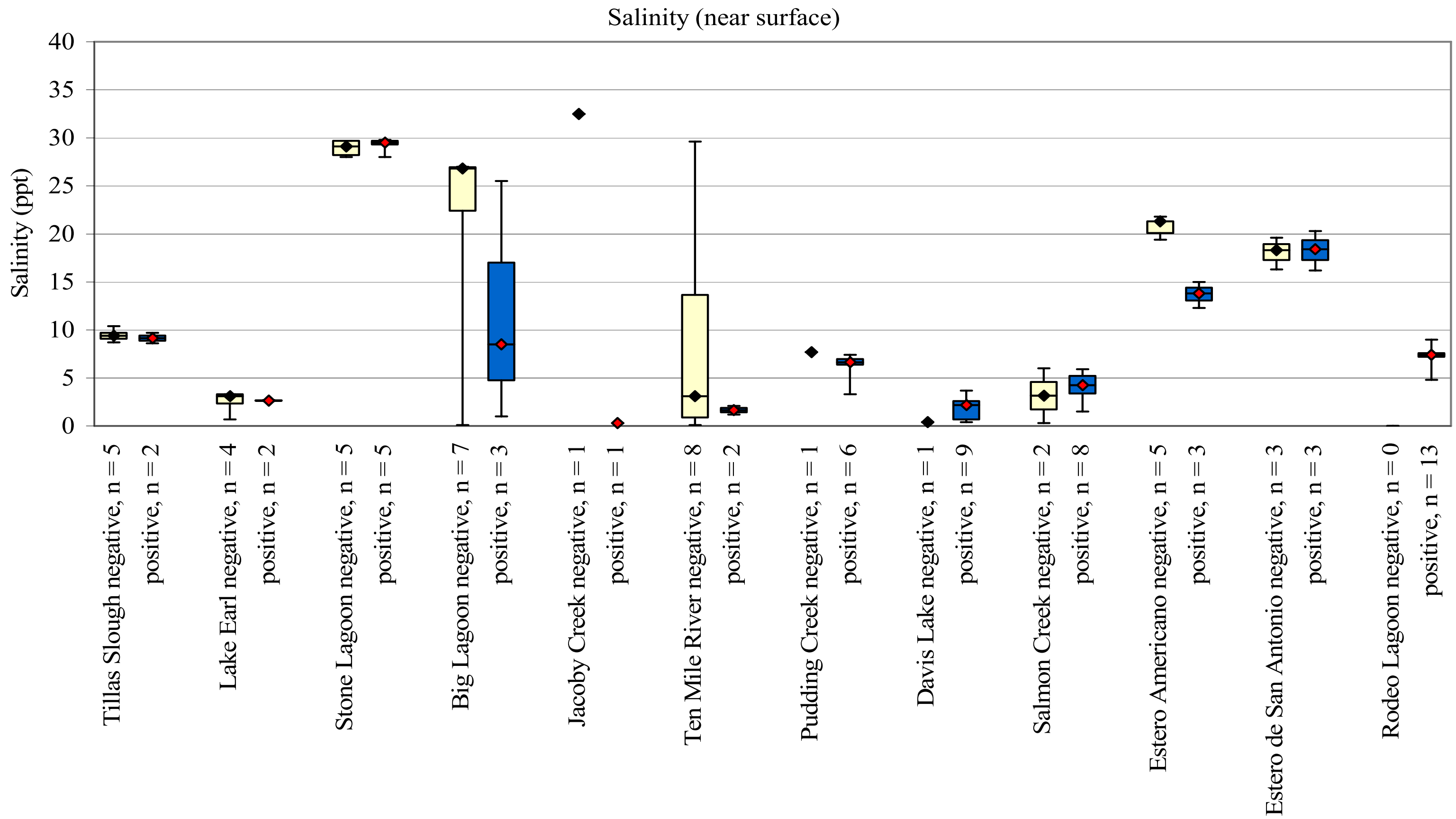

Figure A-1 Salinity measured near the surface during sampling conducted 1996 for waters with confirmed detection of tidewater goby. Boxes represent first and third quartiles, diamond markers represent median, and whiskers indicate the range. Negative detection sites are represented by a light box and black median marker; sites with positive detection are represented by dark blue box and red median marker.

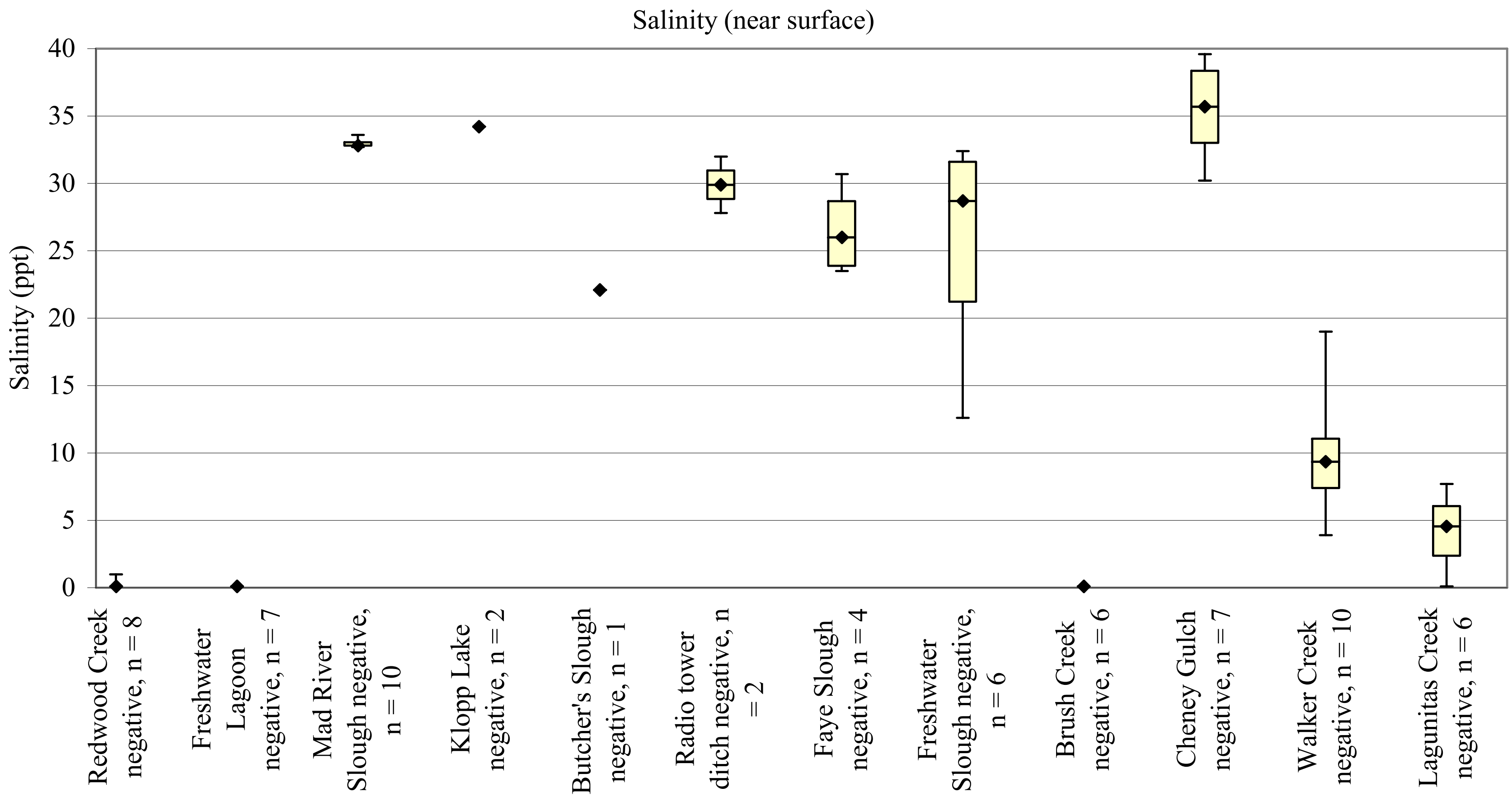

Figure A-2. Salinity measured near the surface during sampling conducted 1996 for waters with no detection of tidewater goby. Boxes represent first and third quartiles, diamond marker represent median, and whiskers indicate the range.

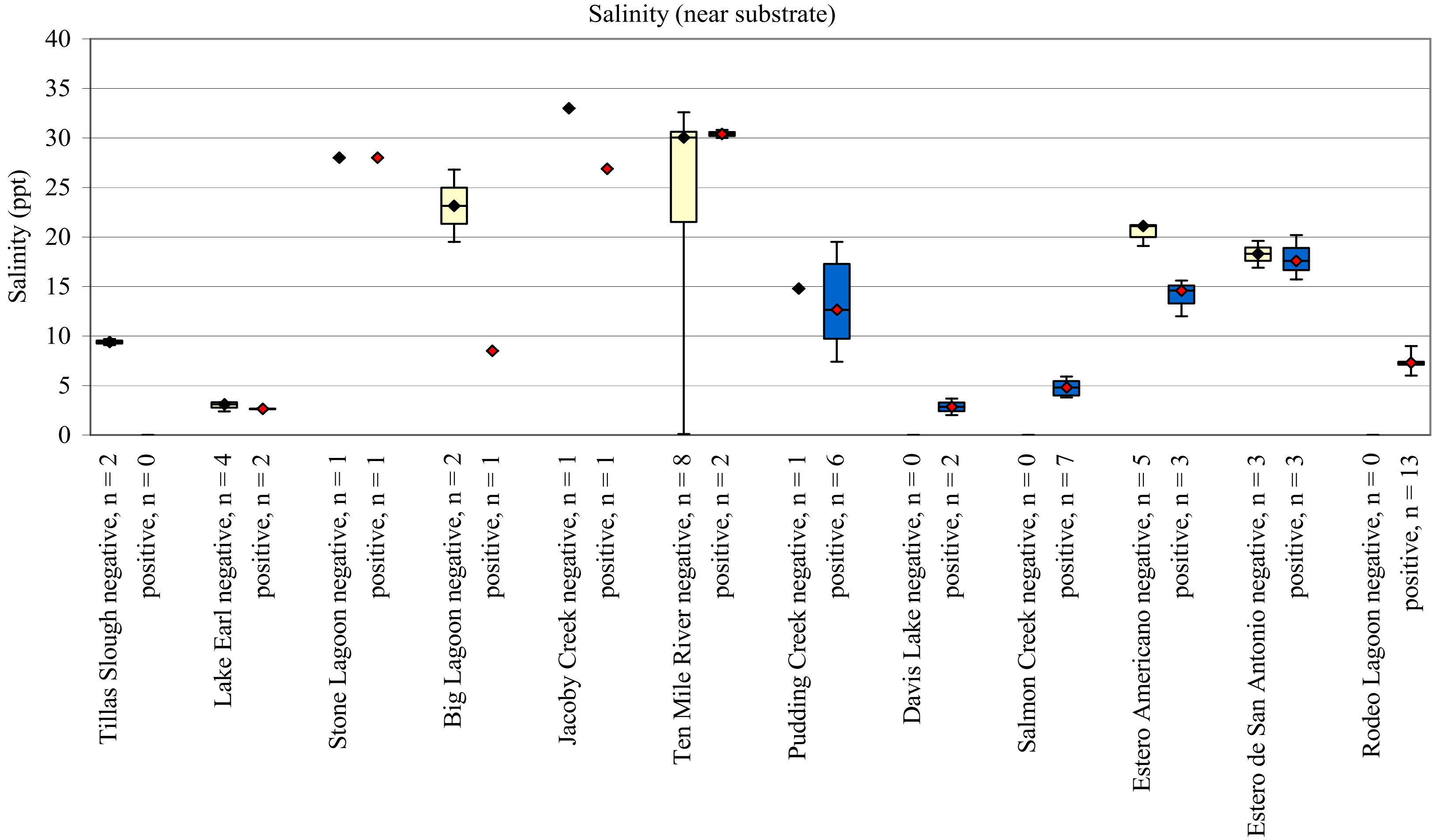

Figure A-3. Salinity measured near the substrate during sampling conducted 1996 for waters with confirmed detection of tidewater goby. Boxes represent first and third quartiles, diamond markers represent median, and whiskers indicate the range. Negative detection sites are represented by a light box and black median marker; sites with positive detection are represented by dark blue box and red median marker.

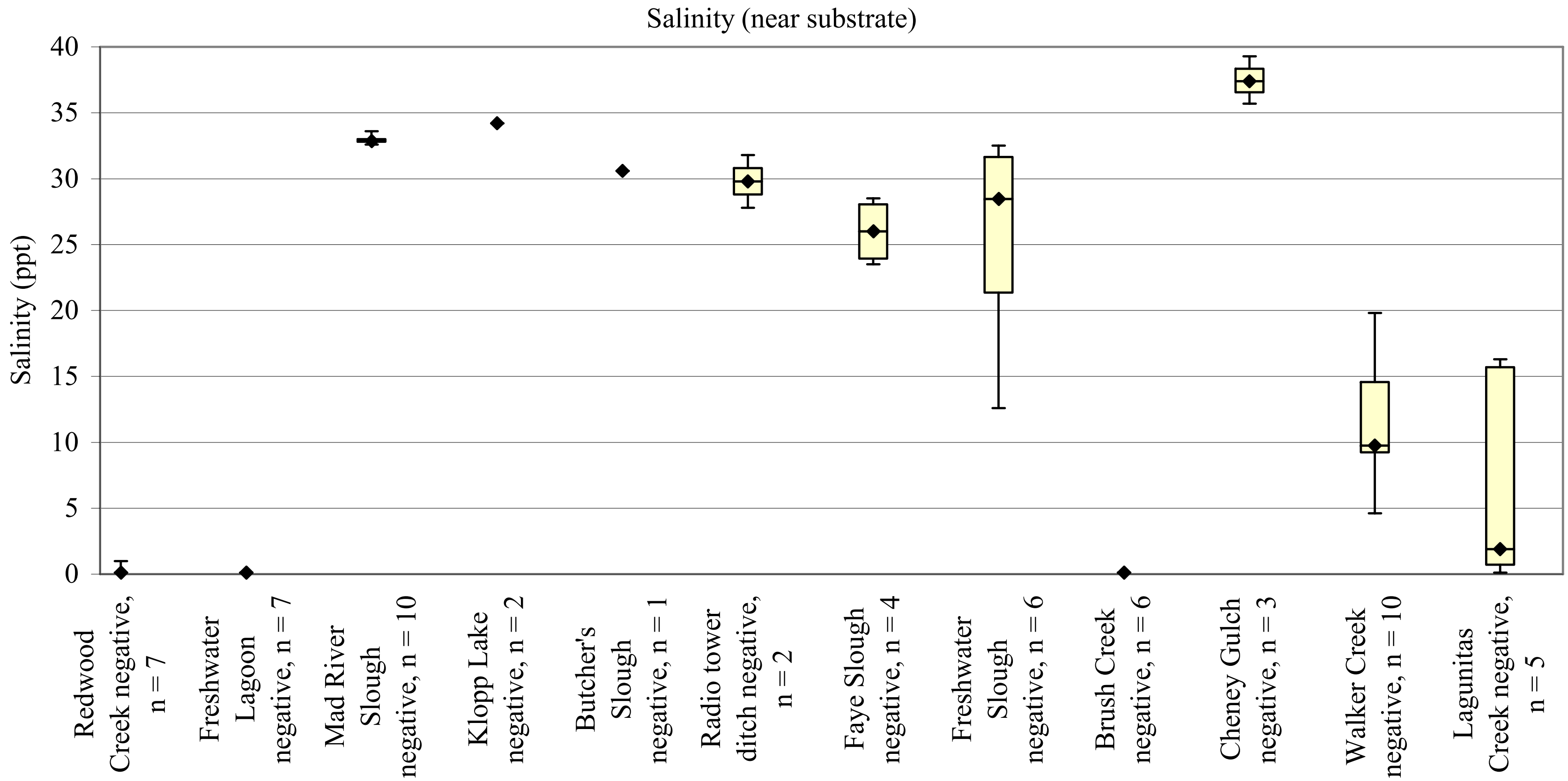

Figure A-4. Salinity as measured near the substrate during sampling conducted 1996 for waters with no detection of tidewater goby. Boxes represent first and third quartiles, diamond marker represent median, and whiskers indicate the range.

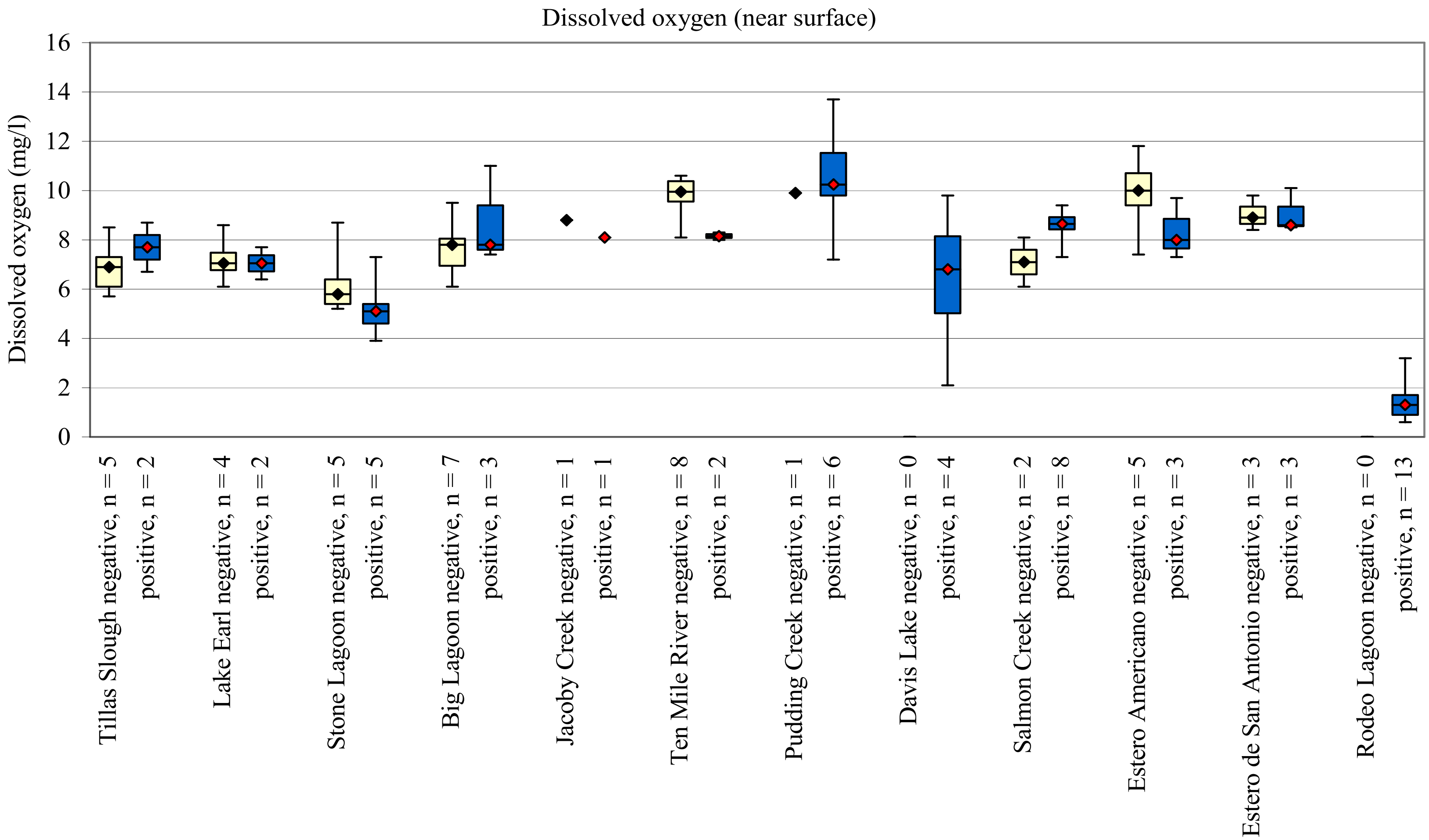

Figure A-5. Dissolved oxygen measured near the surface during sampling conducted 1996 for waters with confirmed detection of tidewater goby. Boxes represent first and third quartiles, diamond markers represent median, and whiskers indicate the range. Negative detection sites are represented by a light box and black median marker; sites with positive detection are represented by dark blue box and red median marker.

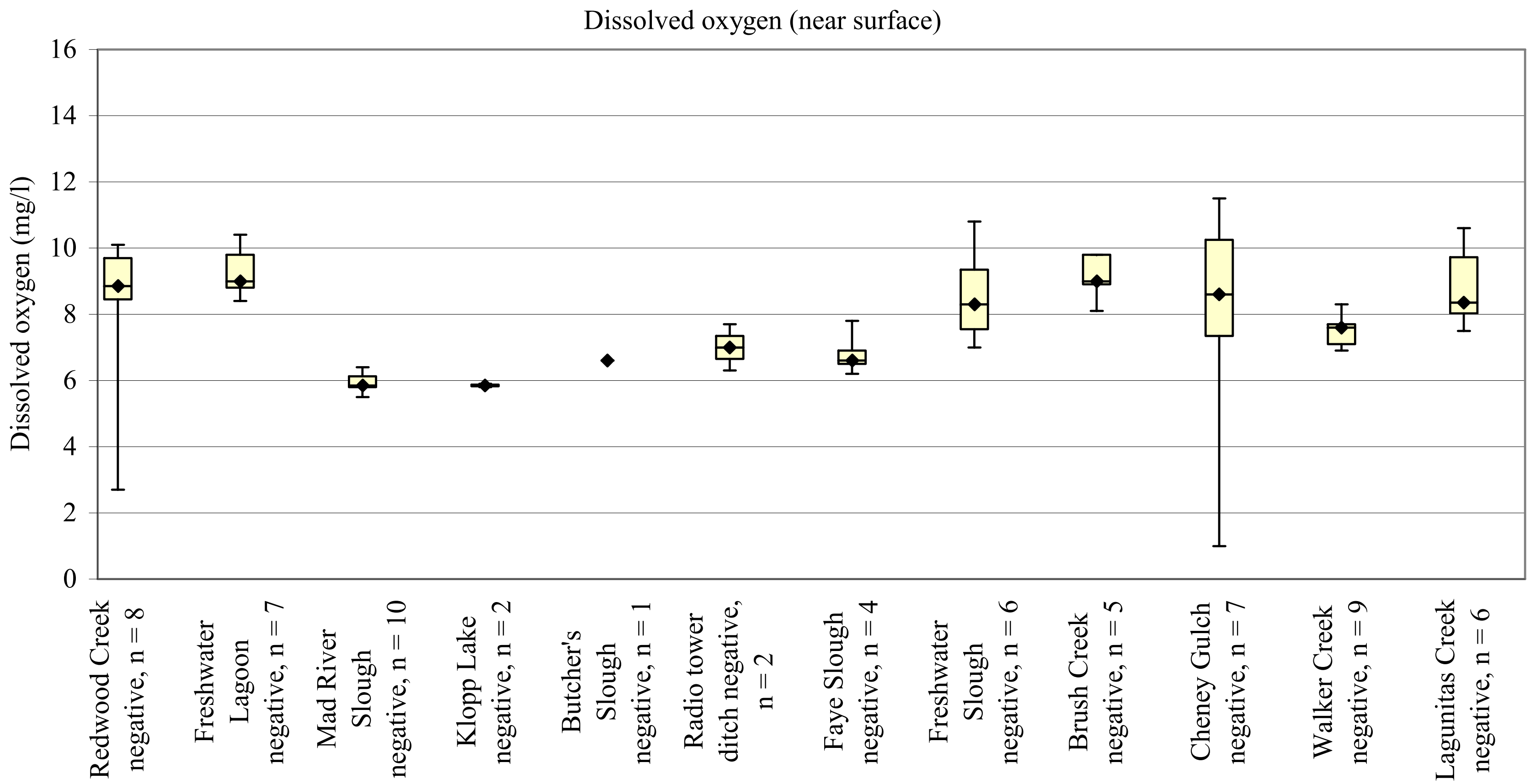

Figure A-6. Dissolved oxygen measured near the surface during sampling conducted 1996 for waters with no detection of tidewater goby. Boxes represent first and third quartiles, diamond marker represent median, and whiskers indicate the range.

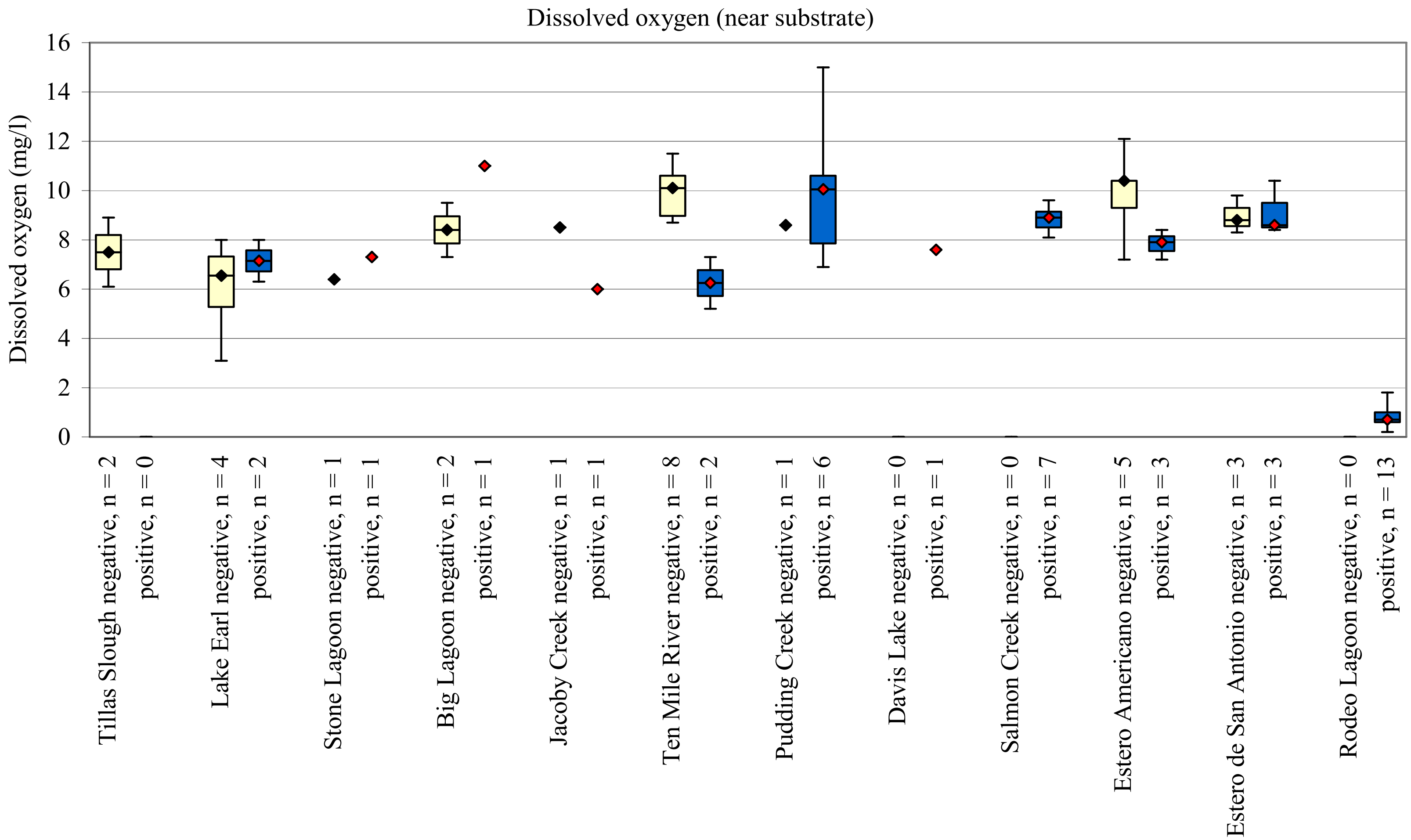

Figure A-7. Dissolved oxygen measured near the substrate during sampling conducted 1996 for waters with confirmed detection of tidewater goby. Boxes represent first and third quartiles, diamond markers represent median, and whiskers indicate the range. Negative detection sites are represented by a light box and black median marker; sites with positive detection are represented by dark blue box and red median marker.

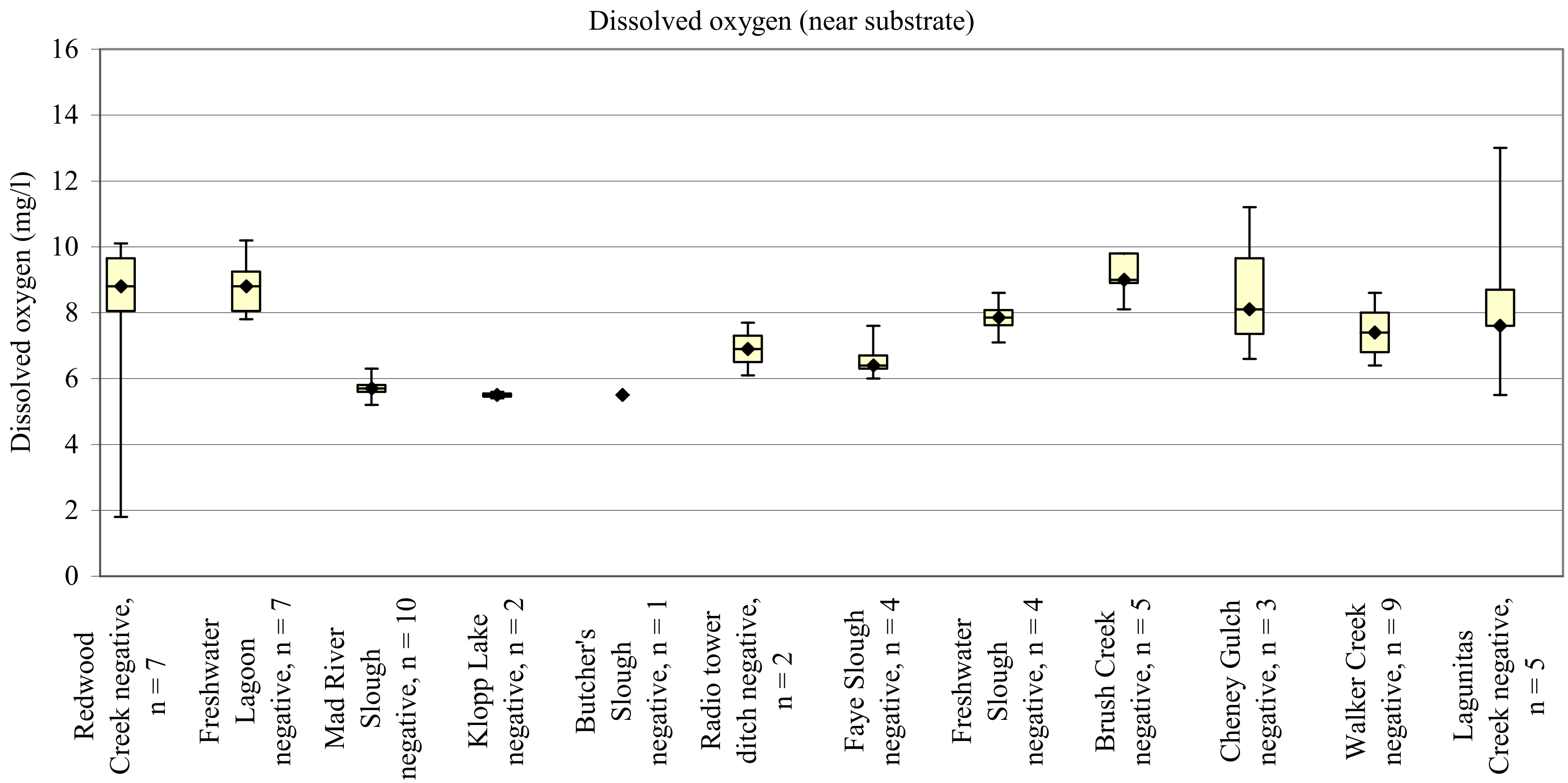

Figure A-8. Dissolved oxygen measured near the substrate during sampling conducted 1996 for waters with no detection of tidewater goby. Boxes represent first and third quartiles, diamond marker represent median, and whiskers indicate the range.

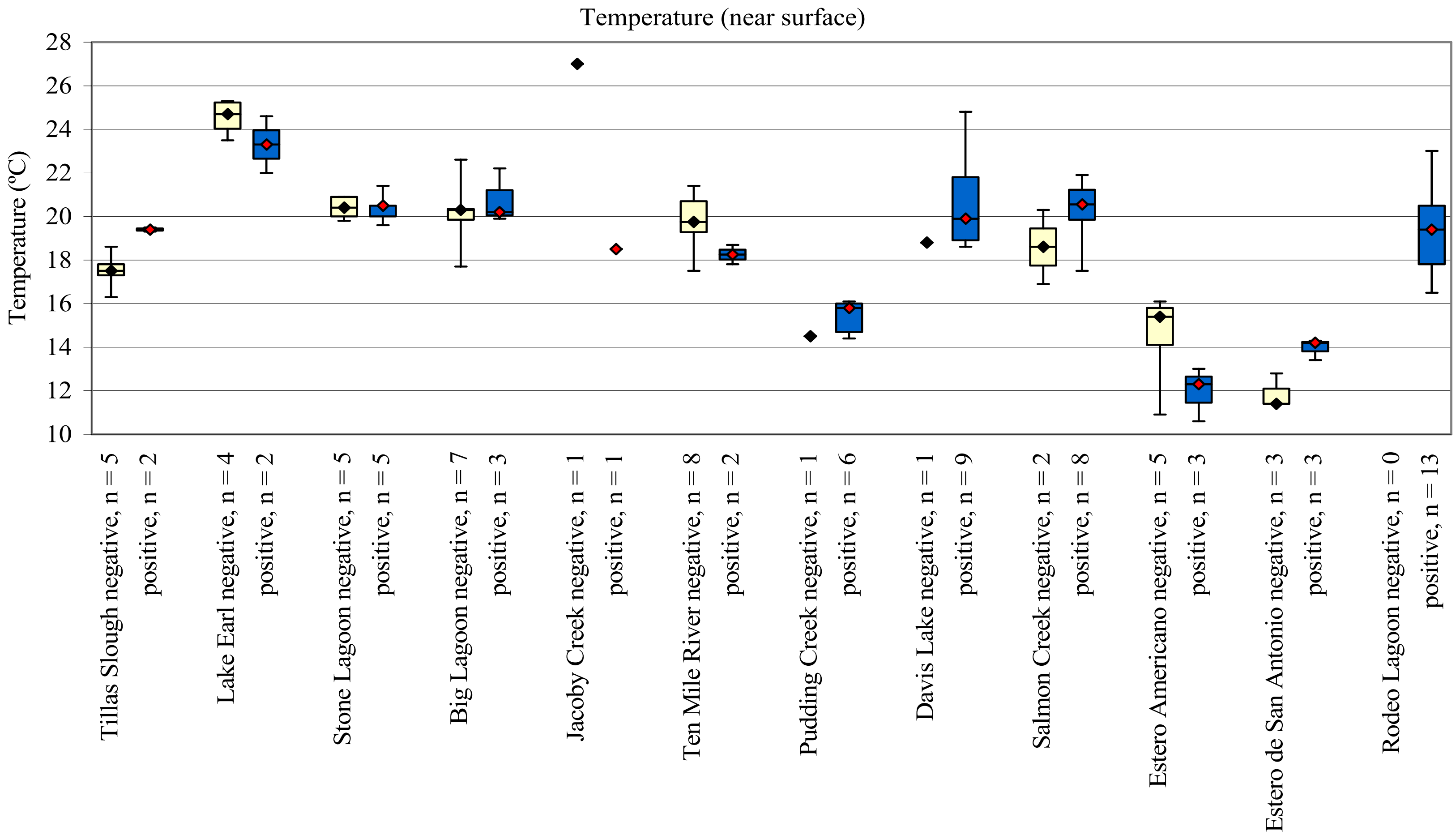

Figure A-9. Temperature measured near the surface during sampling conducted 1996 for waters with confirmed detection of tidewater goby. Boxes represent first and third quartiles, diamond markers represent median, and whiskers indicate the range. Negative detection sites are represented by a light box and black median marker; sites with positive detection are represented by dark blue box and red median marker.

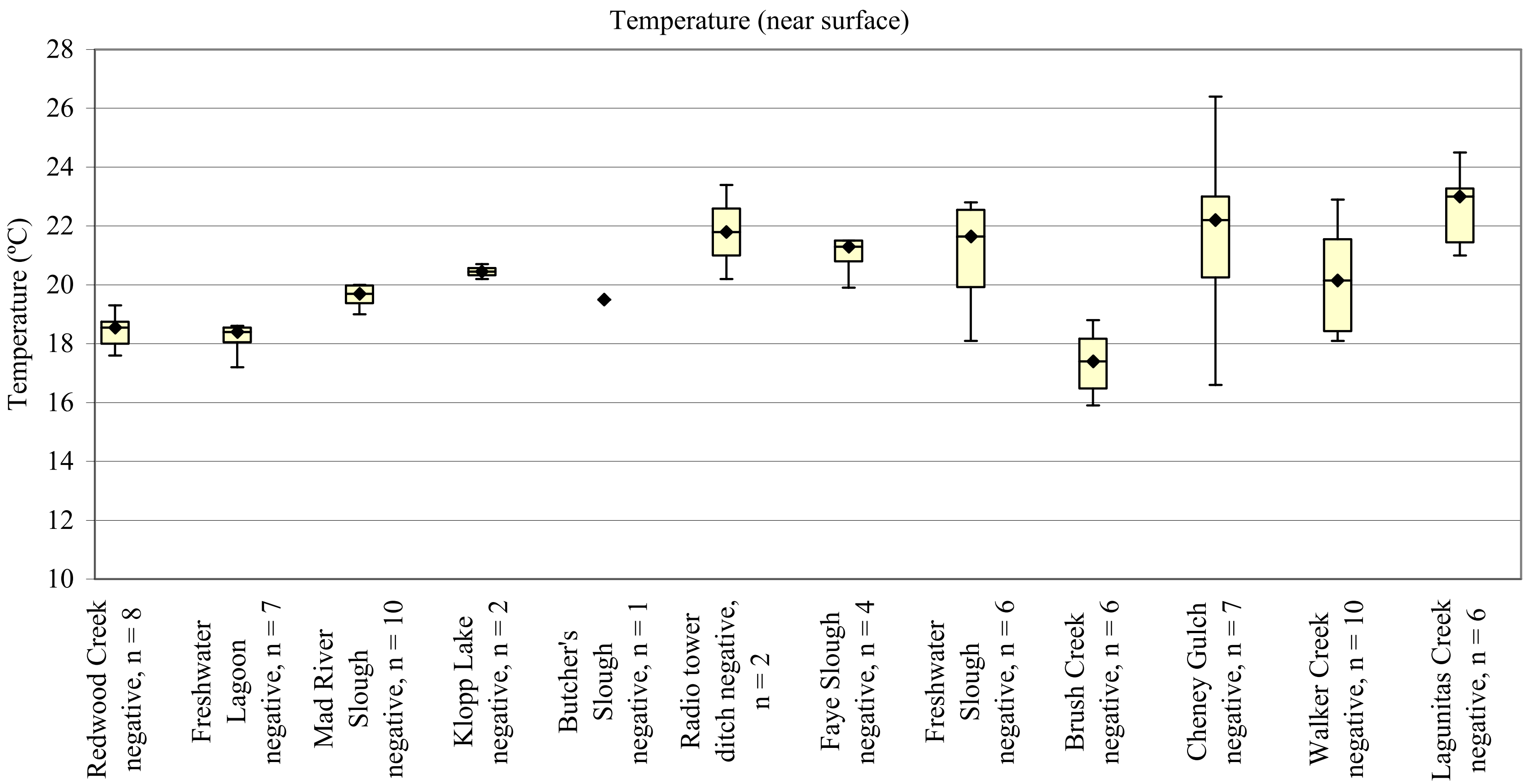

Figure A-10. Temperature measured near the surface during sampling conducted 1996 for waters with no detection of tidewater goby. Boxes represent first and third quartiles, diamond marker represent median, and whiskers indicate the range.

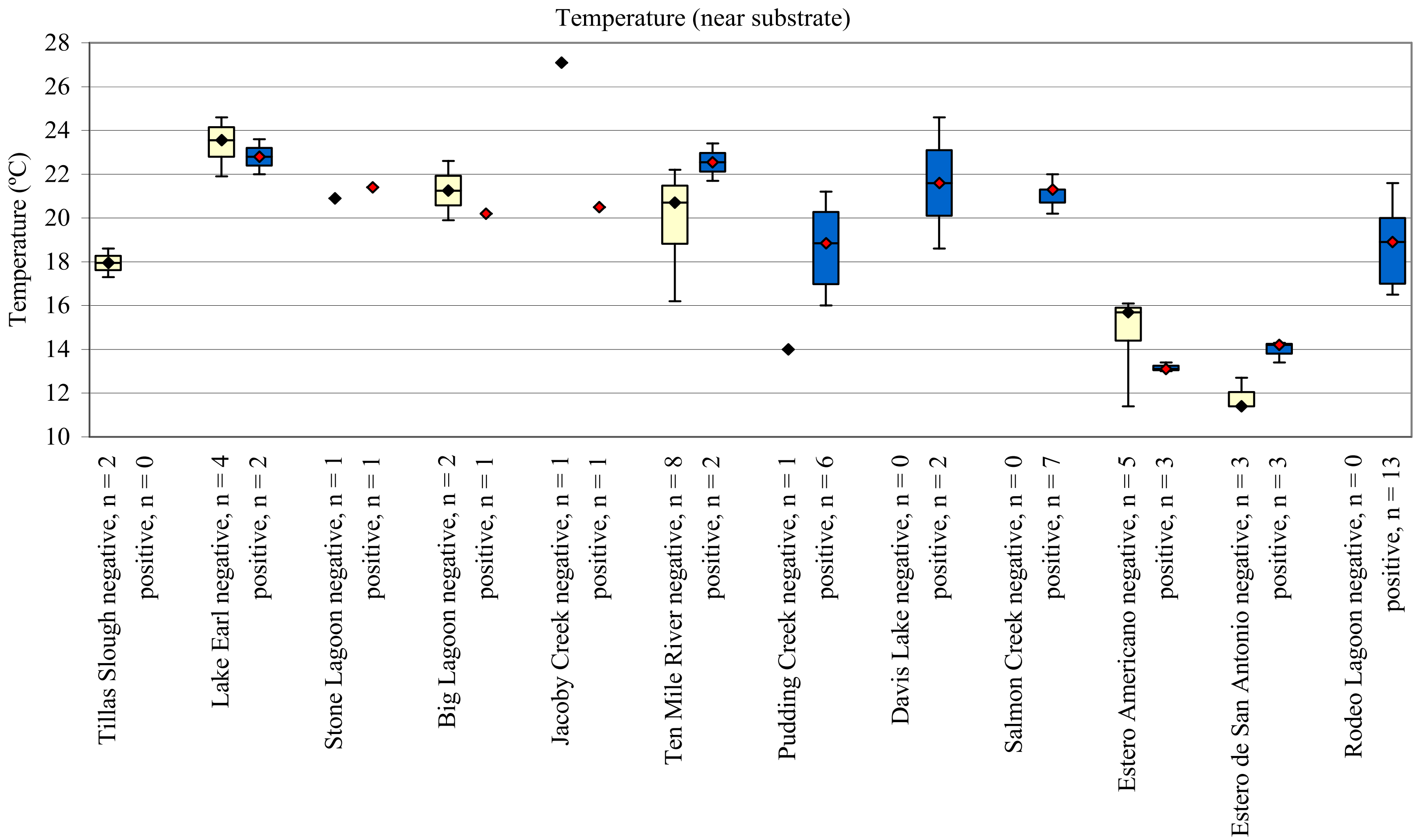

Figure A-11. Temperature measured near the substrate during sampling conducted 1996 for waters with confirmed detection of tidewater goby. Boxes represent first and third quartiles, diamond markers represent median, and whiskers indicate the range. Negative detection sites are represented by a light box and black median marker; sites with positive detection are represented by dark blue box and red median marker.

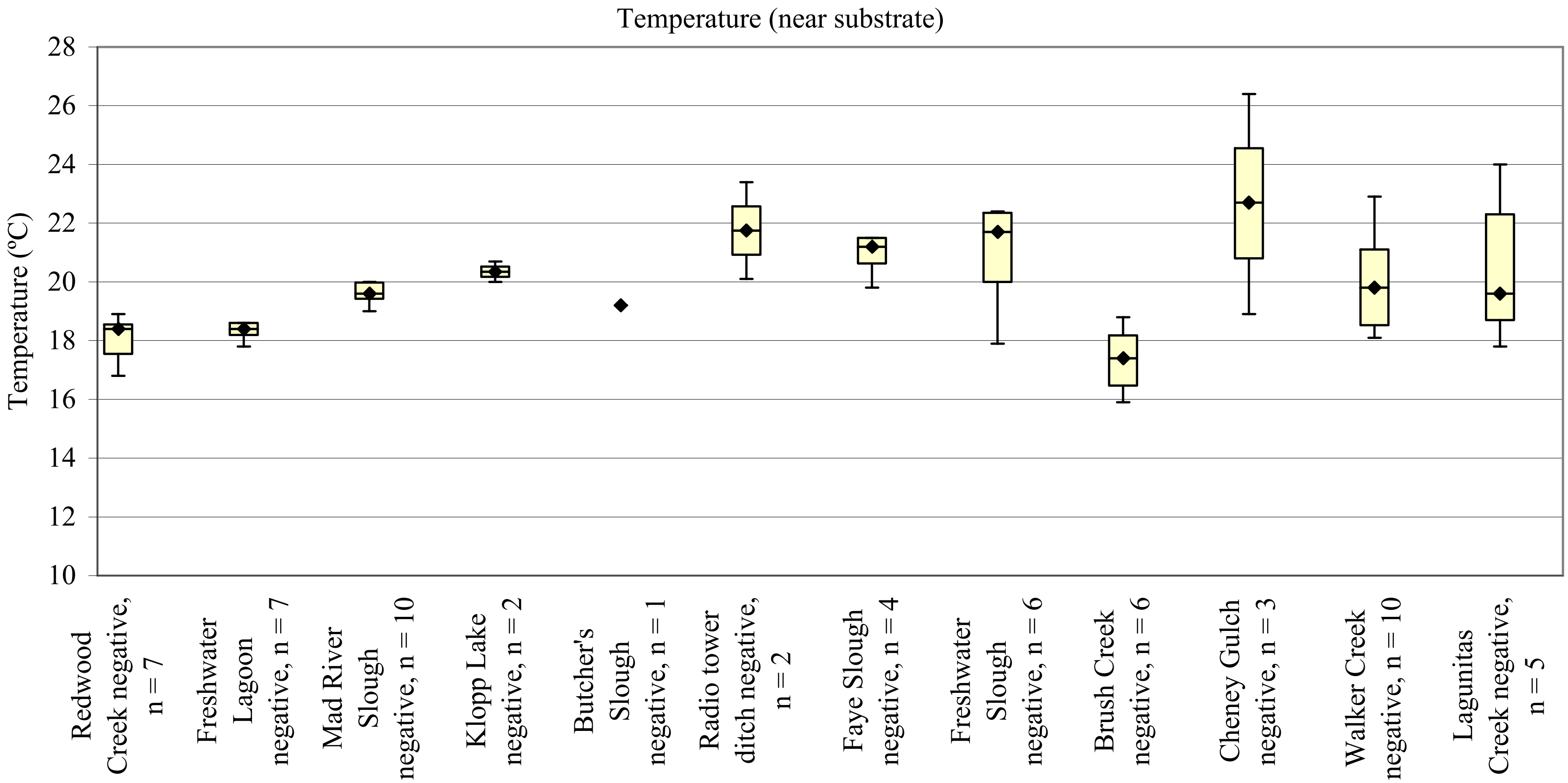

Figure A-12. Temperature measured near the substrate during sampling conducted 1996 for waters with no detection of tidewater goby. Boxes represent first and third quartiles, diamond marker represent median, and whiskers indicate the range.

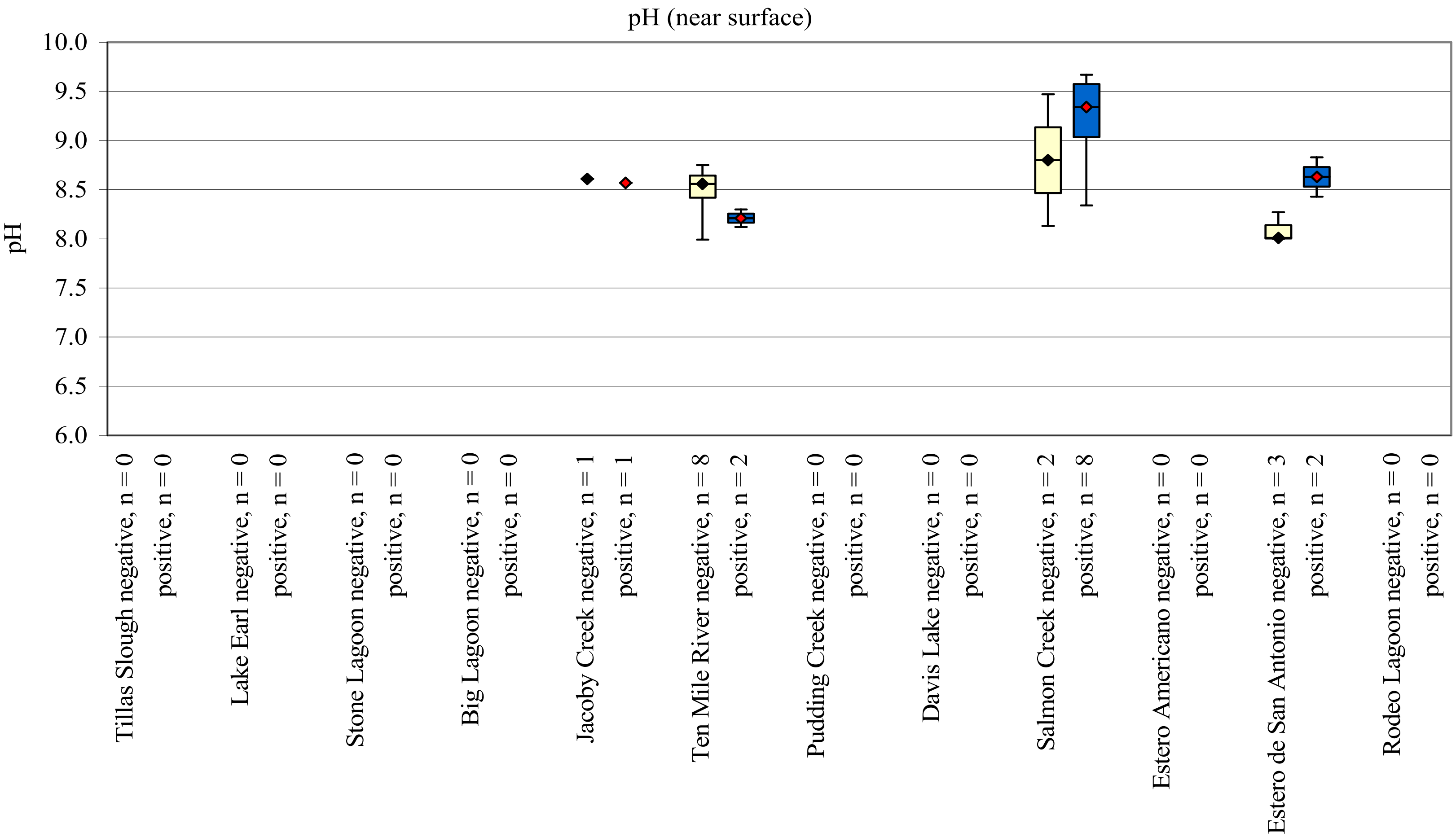

Figure A-13. pH measured near the surface during sampling conducted 1996 for waters with confirmed detection of tidewater goby. Boxes represent first and third quartiles, diamond markers represent median, and whiskers indicate the range. Negative detection sites are represented by a light box and black median marker; sites with positive detection are represented by dark blue box and red median marker.

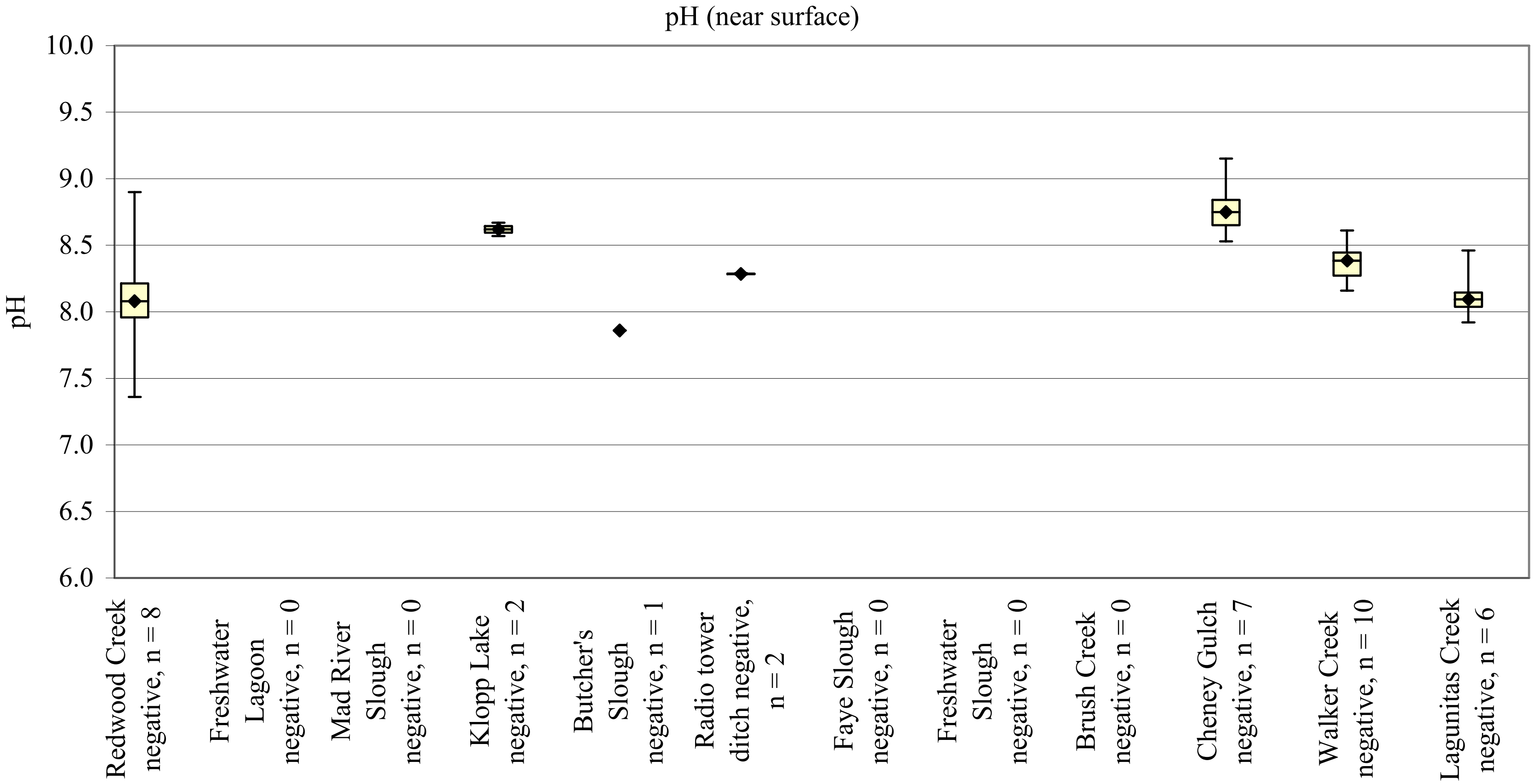

Figure A-14. pH measured near the surface during sampling conducted 1996 for waters with no detection of tidewater goby. Boxes represent first and third quartiles, diamond marker represent median, and whiskers indicate the range.

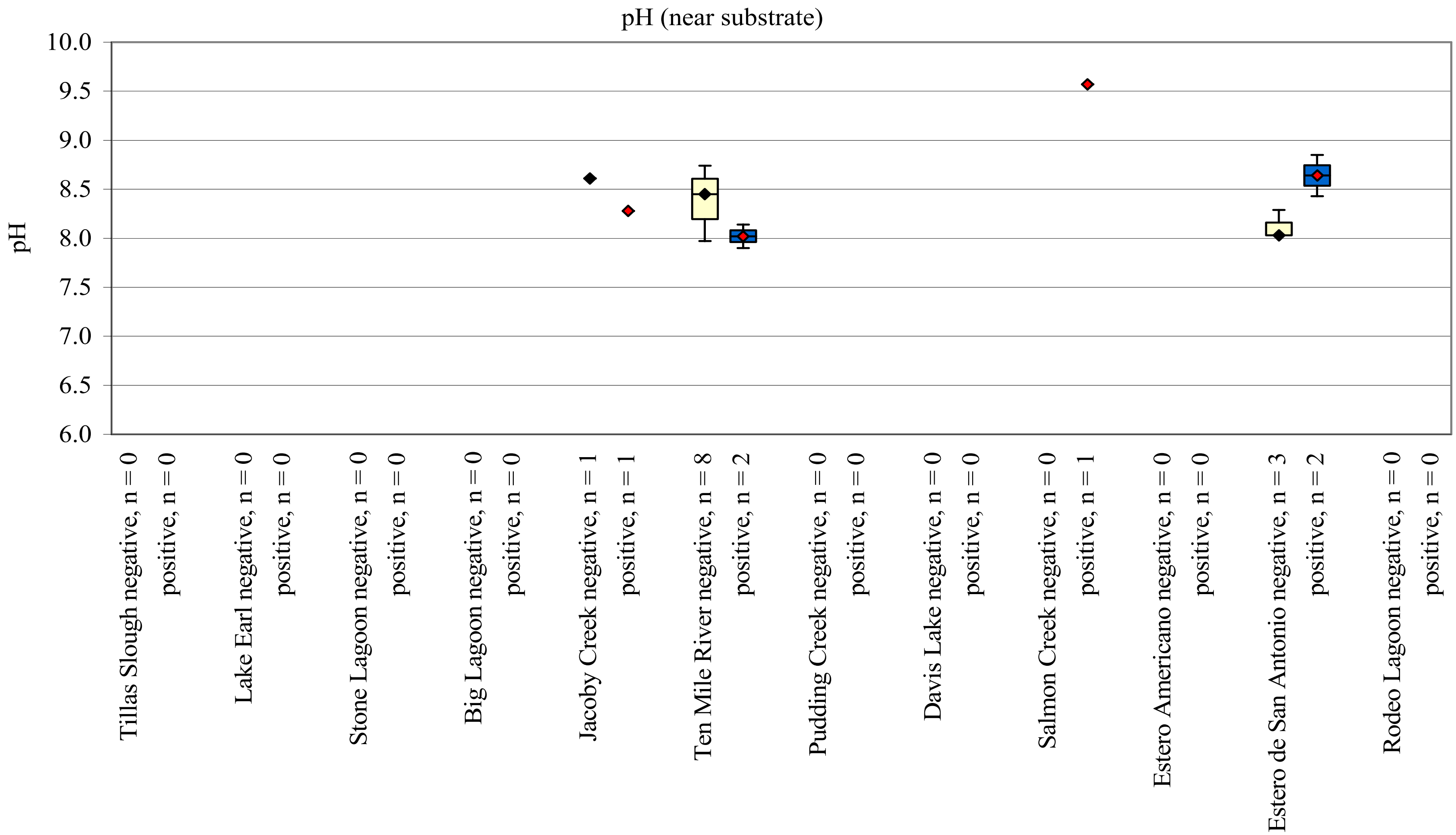

Figure A-15. pH measured near the substrate during sampling conducted 1996 for waters with confirmed detection of tidewater goby. Boxes represent first and third quartiles, diamond markers represent median, and whiskers indicate the range. Negative detection sites are represented by a light box and black median marker; sites with positive detection are represented by dark blue box and red median marker.

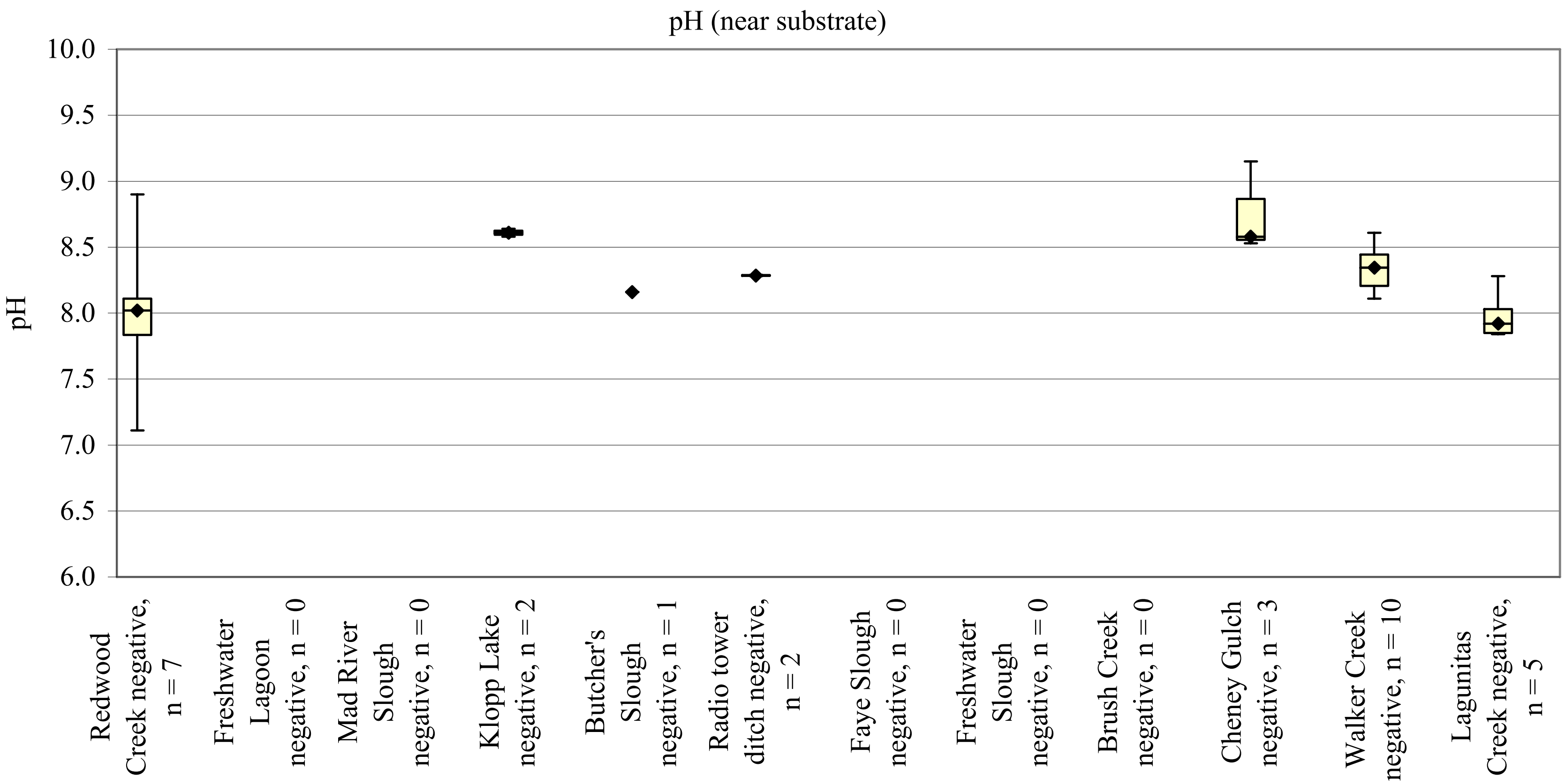

Figure A-16. pH measured near the substrate during sampling conducted 1996 for waters with no detection of tidewater goby. Boxes represent first and third quartiles, diamond marker represent median, and whiskers indicate the range.

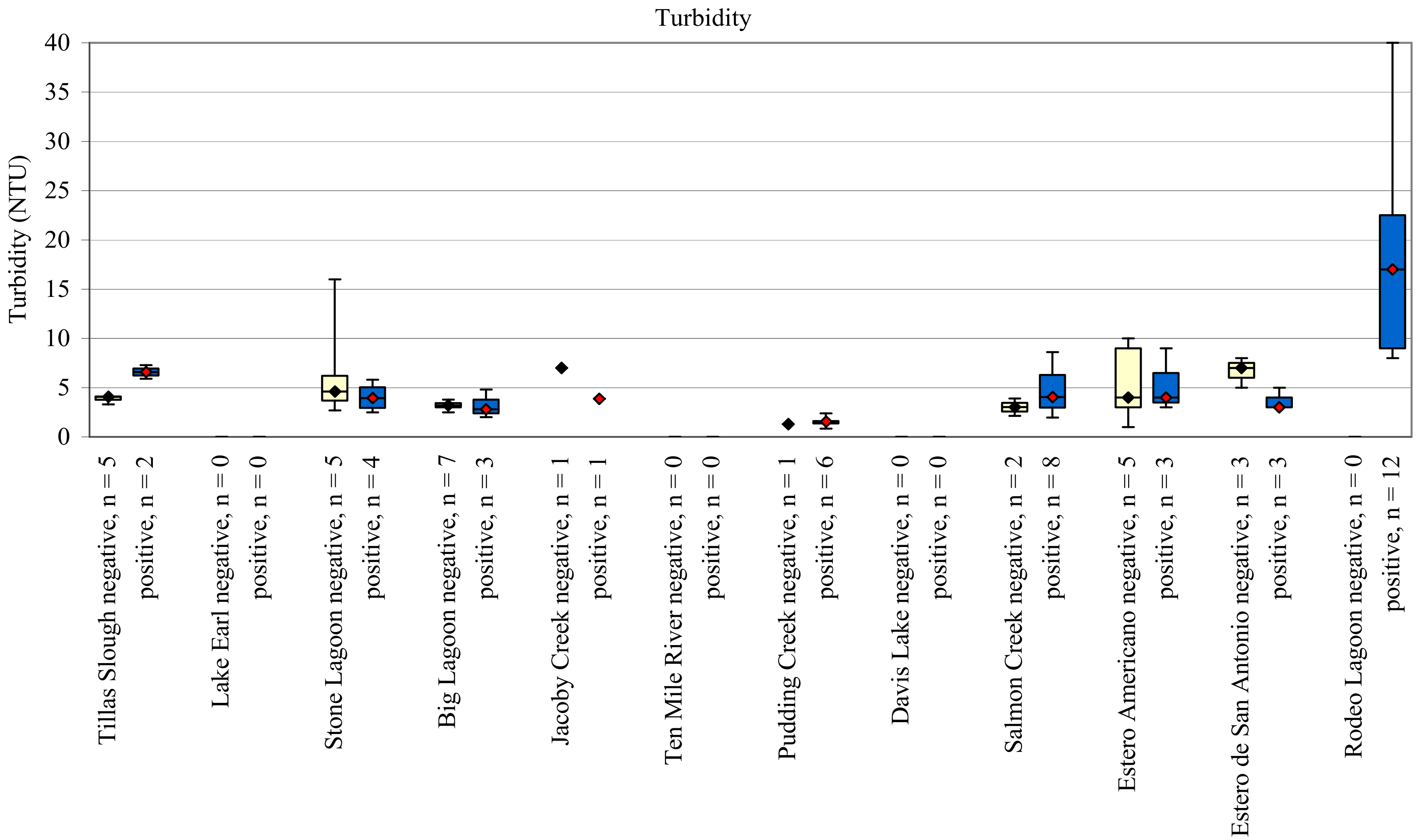

Figure A-17. Turbidity measured during sampling conducted 1996 for all waters with confirmed detection of tidewater goby. Boxes represent first and third quartiles, diamond markers represent median, and whiskers indicate the range. Negative detection sites are represented by a light box and black median marker; sites with positive detection are represented by dark blue box and red median marker.

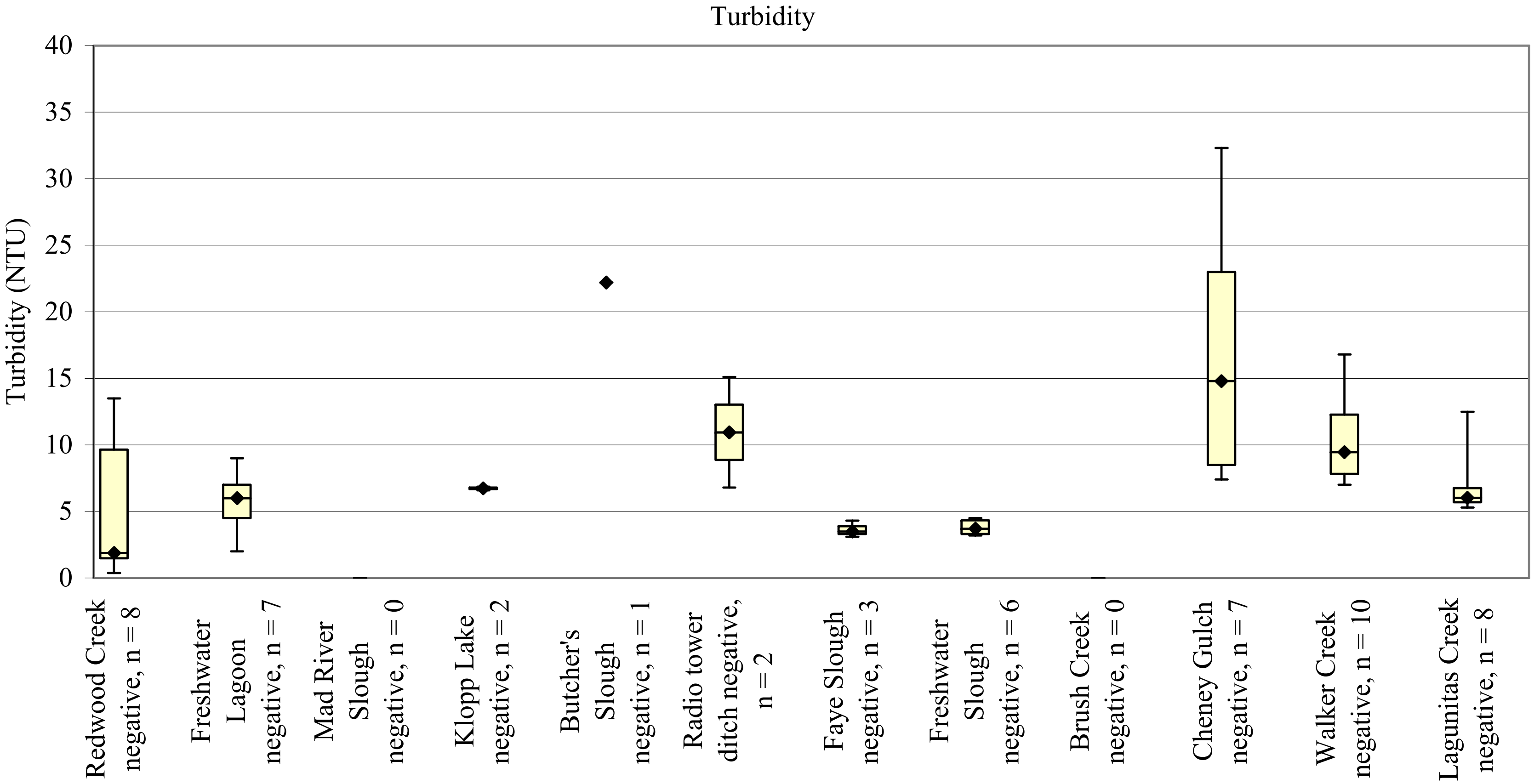

Figure A-18. Turbidity measured during sampling conducted 1996 for all waters with no detection of tidewater goby. Boxes represent first and third quartiles, diamond marker represent median, and whiskers indicate the range.